A Practical Guide for Detecting Single-Phasing on a Three-Phase Power System

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A PRACTICAL GUIDE FOR DETECTING SINGLE-PHASING ON A THREE-PHASE POWER SYSTEM

Understanding and predicting the per phase magnitude and angle of phase to phase, phase to neutral, positive, negative, and zero sequence voltage and current generated during the loss of one or two phases of a radial three phase system is fundamental to the application of protection schemes designed to detect the same. Many papers have been presented on sequence quantities available during specific faults, but protection engineers will find fewer references deal exclusively with system conditions and resultant sequence quantities generated during a single phase condition. This paper is provided as reference for that condition and includes suggested detection and protection methods for each application.

SCOPE

The loss of a phase simply means loosing the definition of that phase's voltage level and while there is some tendency to assume that the phase voltage falls to 0 (relative to neutral in most applications), this may not be the case. There are multiple elements in the power system providing paths and mechanisms to re-energize the lost phase(s) from the remaining phase(s), sometimes in a manner that so closely resembles the lost phase that the condition is virtually undetectable. This lack of definition of the final voltage of the lost phase can make detection of the phase loss condition difficult. The purpose of this paper is to assist the engineer in understanding the difficulties.

Toward the purpose of developing a better understanding of the phase loss condition, this paper will identify some target radial system transformer and load configurations and examine the effects of opening a conductor (or fuse) in one or two phases at various points in the system. The paper will investigate how lost phases may be re-energized from loads, including motors, electrical interphase coupling in delta connections in transformers, and magnetic interphase coupling in three phase core and shell form transformers. One leading interest of the paper will be transformer effects on phase loss conditions. The focus of this analysis will be power transformers, but voltage instrument transformers phase loss is also covered. Resultant quantities for specific phase loss conditions are predicted through inspection and calculation and then verified through practical tests where possible using a configurable three phase test source and a set of test transformers. The test transformers included a three-phase three legged core form transformer configurable for delta or wye connections on both sides of the transformer, and a set of single-phase transformers connected for the same conditions, and are described in Appendix 1.

For each system examined some readily available economical detection options found in multifunction protection systems will be discussed, such as 51Q/46, 51N, 50U (undercurrent), 27, 47, 59N, and 59P.

SYSTEM TO BE ANALYZED

To avoid a confusing analysis of too many permutations of the various power system configurations that exist, this paper addresses the more common solidly grounded system with two winding delta and wye connected transformers. In the sections to follow, in general, a phase loss is assumed upstream of a transformer, and the work will examine the system conditions that will be seen at the terminals of the transformer on both the primary and secondary during the phase loss condition.

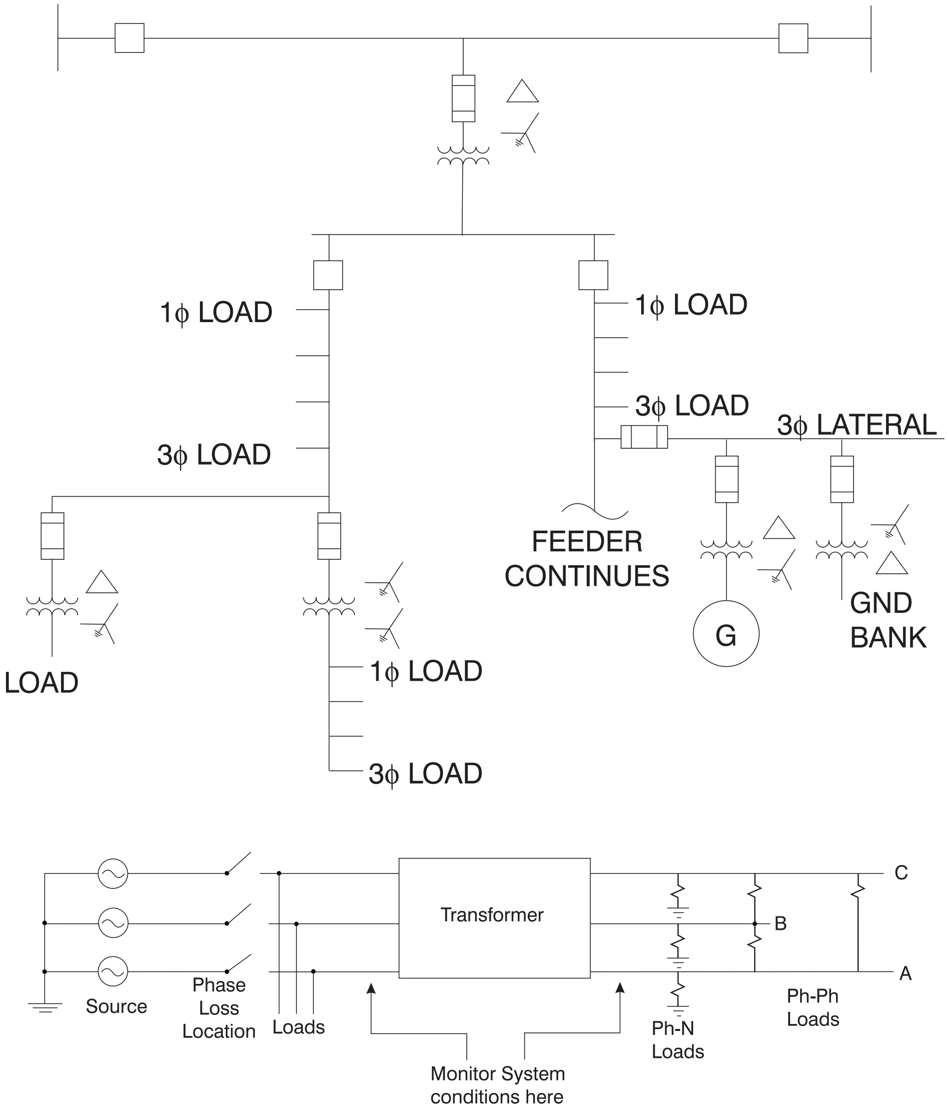


Figure 1: System Under Examination

Ungrounded and impedance grounded systems, Scott-T transformers, and three winding transformer analysis will be left to the reader to reason through, in part by applying the concepts developed in this paper.

Per Unit Quantity References Used in Paper

In all tables except for Table 3, the voltages are per-unitized on a phase to neutral basis. In this paper, under normal conditions V_{LL} is 1.732 ($\sqrt{3}$). To assist the reader, the V_{LL} magnitude is also shown after division by $\sqrt{3}$ to give a feel for the comparable phase to neutral quantity.

When sequence component quantities are given in the paper, they are provided with V_{AN} as the base reference for both magnitude and angle. If the reader has a phase to phase VT, mental adjustments will be required to account for phase angle shifts (+/-∠30) and magnitude shifts (÷ or x √3) required depending on VT ratios and various calculation adjustments that occur within the relay in use.

Sequence Component Measurements for Phase Loss

The loss of any phase may result in a notable reduction of voltage on one or more phases and a corresponding increase in voltage unbalance. In modern numerical multifunction relays the standard measures available for phase loss detection are negative sequence voltage V_2 (device number 47), zero sequence voltage V_0 (device number 59N), and undervoltage (27_{LL} or 27_{LN}). Also associated with phase loss detection is negative sequence current I_2 (device number 46, sometimes also called a 51Q), zero sequence current I_0 (or alternatively $3I_0$ or I_G, device 51N or 51G), and undercurrent (50U). This paper identifies the phase voltages and currents, and basic sequence quantities V_2 and V_0, and in a couple of cases, I_2 and I_0, that arise during a variety of phase loss conditions.

The paper leans on an intuitive and fairly physical based understanding of what will occur during a phase loss condition. The more mathematical sequence (= symmetrical) component analysis of the open phase condition is required for the complete solution of anything more than the most simple circuits. However, sequence component analysis can prevent a physical understanding of what is occurring and does not predict some aspects of phase to phase coupling found in some three phase transformer configurations. In Appendix 2 a sequence component approach is given to open phase condition.

Even if not performing circuit analysis using sequence component, the equations for sequence / phase conversion will be used when determining relay response to system conditions. The equations, for voltages, have the form of:

$$\begin{vmatrix} V_0 \\ V_1 \\ V_2 \end{vmatrix} = \frac{1}{3} \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \cdot \begin{vmatrix} V_A \\ V_B \\ V_C \end{vmatrix} \quad \text{and} \quad \begin{vmatrix} V_A \\ V_B \\ V_C \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{vmatrix} \cdot \begin{vmatrix} V_0 \\ V_1 \\ V_2 \end{vmatrix} \qquad \text{Eq. 1}$$

$$(a = 1\angle 120, \quad a^2 = 1\angle 240)$$

Current equations have the same format of course. Reference 1 provides a Microsoft Excel spreadsheet that offers a relatively easy means of performing the calculations described above. If one needs an explanation of sequence components, refer to many common electric power engineering texts.

This paper presents sequence quantities in terms of I_0, I_2, V_2 and V_0, rather than 3x terms such as $3I_0$. While most (if not all) manufacturer's relays are set in terms of $3I_0$, there is some variation between relay manufacturers with respect to the use of "3x" or "1x" in the V_0, I_2, and V_2 quantities in relay settings (e.g., Is the negative sequence function set in terms of V_2 or $3V_2$? Is the zero sequence function set in terms of V_0 or $3V_0$?).

Phase Loss Analysis vs. 60FL / LOP Logic

Certain secondary derived sequence quantities (such as V_2/I_2, V_2/V_1, I_2/I_1, and change of $V_{0,1,2}$, $I_{0,1,2}$ etc.) and a more involved logic schemes than discussed herein are used in many numerical relays for a function sometimes referred to as a "60FL (Fuse Loss)" or "LOP (Loss of Potential)." A basic concept of many 60FL/LOP functions is that high V_2 with low I_2 is highly indicative of a single or dual phase loss. Other 60FL logic schemes look for changing sequence quantities, such as a decrease in V_1 without an increase in I_1 may indicate a fuse loss. These algorithms are aimed at sensing VT fuse loss conditions, not system phase loss conditions. Toward this purpose, the algorithms in general assume that when a phase is lost to the relay's VT, the VT secondary voltage falls to 0V, which is normally true for VT circuits, but may not be true in a power system where there are many paths for the remaining phase(s) to back-feed into the lost phase(s) and partially or entirely recreate the lost phase(s). While the 60FL function might be used to sense a power system phase loss, this paper does not offer an analysis of using the various 60FL logics in the various relays on the market for this purpose.

Alternative Measurements for Phase Loss

Relays are on the market (typically less expensive) that measure phase loss, reverse phase sequence, and/or voltage unbalance (and currents too) with techniques other than sequence components. The algorithms tend to be based on some filtered measure of maximum over average of voltages developed by analog circuits. The algorithms tend to be manufacturer specific and poorly documented. These alternative relays will not be considered in this paper and this paper restricts analysis to basic phase and sequence components that may arise during phase loss conditions.

Normal System Conditions

One needs to ensure relay settings are not issued that will result in trips during normal system unbalances, so for reference, below is a possible 'worst case' system unbalance.

Voltages

Under normal ideal operating conditions, per-unitizing on the phase-neutral values, voltages at the primary and secondary, assuming ABC rotation, will be:

Table 1

Normal System Conditions					
V_{AN}	$1.00\angle 0$	V_{AB}	$1.732\angle 30$	$V_{0,LN}$	0
V_{BN}	$1.00\angle -120$	V_{BC}	$1.732\angle -90$	$V_{1,LN}$	$1\angle 0$
V_{CN}	$1.00\angle 120$	V_{CA}	$1.732\angle 150$	$V_{2,LN}$	0

By most utility operating practices, the power system as measured at the end user will almost always operate at $\pm$5% from nominal, with short excursions to $\pm$10%. The allowed difference between phases is typically not well defined but is simply inferred from the allowed magnitude range. Excursions to one phase high by 10% and another low by 10% should be exceedingly rare, so a likely worst case condition as far as the voltage imbalance calculation is concerned is that one phase is high 5% and another is low 5%. The angles between phases is 120 degrees at every generator, but load imbalances and phase impedance variances may make for a slight difference in the voltage drop and phase angle from one phase to another. A likely worst case error derived from some sample load drop calculations is that the more highly loaded phase with lower voltage (0.95pu) lags the normal 120 degrees by an additional 3 degrees and the more lightly loaded phase with higher voltage (1.05pu) leads the normal 120 degrees by an additional 3 degrees. The results are shown in the upper half of table 2.

For a comparison, the lower half of table 2 shows the system phase voltages that would arise assuming 10% V_2 and 5% V_0. (V_0 was set lower than V_2 because it is difficult to build up large zero sequence voltages on a solidly grounded power system, especially when voltage is measured local to the equipment, where a neutral shift may be hard to measure when the ground plane itself may become elevated). This shows some abnormally high and low phase voltages that most would say will not occur very often in a power system, indicating these are abnormally high V_2 and V_0 conditions.

Table 2

Example phase-neutral unbalanced condition (Nominal V_{LN}=1pu): >> Starting with given 'worst case' phase voltages and finding resultant sequence quantities					
V_{AN}	1.00∠0	V_{AB}	1.714∠27.7 (/√3=0.989)	$V_{0,LN}$	0.041∠136.8
V_{BN}	0.950∠-123	V_{BC}	1.678∠-88.1 (/√3=0.969)	$V_{1,LN}$	0.999∠0.1
V_{CN}	1.050∠123	V_{CA}	1.802∠150.7 (/√3=1.040)	$V_{2,LN}$	0.043∠-44.1
>> Starting with given sequence quantities, showing possible abnormally high phase unbalance that would occur					
V_{AN}	1.15∠0	V_{AB}	1.825∠25.3 (/√3=1.054)	$V_{0,LN}$	0.05∠0
V_{BN}	0.926∠-122.7	V_{BC}	1.559∠-90.0 (/√3=0.900	$V_{1,LN}$	1.00∠0
V_{CN}	0.926∠122.7	V_{CA}	1.825∠154.7 (/√3=1.054)	$V_{2,LN}$	0.10∠0

As mentioned before, the paper uses V_{AN} as a reference so the nominal phase to phase value is √3. To assist readers who feel more comfortable with V_{LL} =1pu, phase to phase values are shown after division by √3. Also for users that think in terms of phase to phase voltages as a point of reference, assume alternatively that V_{AB} is high by 5% and V_{BC} is low by 5%, setting V_{AB} =∠30 and V_{BC} =∠-90, and calculating the resultant V_{CA}:

Table 3

Example phase-phase unbalanced condition (Nominal V_{LL}=1pu)					
V_{AN}	0.607∠3.1 (x√3=1.052)	V_{AB}	1.050∠30	$V_{0,LL}$	0
V_{BN}	0.578∠-121.7 (x√3=1.000)	V_{BC}	0.950∠-90	$V_{1,LL}$	1.000∠31.7
V_{CN}	0.549∠123.5 (x√3=0.952)	V_{CA}	1.004∠154.9	$V_{2,LL}$	0.058∠0.0

From these two tables, it appears that a V_2 threshold of 10% of nominal should be very resistant to picking up during normal system conditions. Of course an appropriate time delay should be added to prevent operation during transient fault conditions, large load inrushes, and single-phase-at-a-time field load transfers and switching.

If these "worst case" conditions do not match the reader's application, such as an industrial facility with large unbalances on the end of a weak line, see Reference 1 for some assistance in performing the various calculations associated with converting the reader's worst-case condition between line-neutral, line-line, and sequence components.

Currents
There is no easy method of determining a level of I_2 that would be unacceptable due to normal system unbalances and the normal system daily and seasonal load swings, especially at medium and low distribution voltages; e.g., under light loading a phase loss may yield I_2 so low that it that may be below normal acceptable I_2 under heavy loading. Even an nominal ratio of I_2/I_1 may be difficult to determine. For instance, three phase motor loads have an interesting feature of having a much lower Z_2 than Z_1 (except during the motor starting period), so as V_2 increases, I_2 rises quickly, which may skew the I_2/I_1 ratio depending on the present 3 phase motor load and the present V_2.

TRANSFORMER THEORY
The loss of one or two phases of the primary feeding a transformer has different effects on the resultant primary and secondary voltages depending on the transformer winding configurations (i.e., delta or wye), whether the three phases are comprised of three single phase transformers (called a 3x1-phase bank here-in), a 3 legged core form bank, a 4 legged core form bank, or a 5 legged shell form bank.

In this paper, the "primary" and "secondary" will refer to the high and low voltage sides, respectively, of the transformer. In most applications the primary is the power source side, but conditions arise where the secondary may be the power source side.

Banks Comprised of Multiple Single Phase Transformers (3x1-Phase)
If the transformer bank is comprised of three (or two in the case of an open delta VT) interconnected stand-alone single phase transformers, transformer theory is mainly a simple application of voltage and current ratios. The interaction between phases in the transformer is due strictly to the winding and load connections and there is no phase to phase magnetic coupling as found in shell form and core form three phase transformers.

Three Phase Banks ("Core Form" and "Shell Form")
In three phase transformers it is necessary to understand the core design if one is to predict the results of phase loss conditions because the core provides phase to phase magnetic coupling that will affect the phase loss conditions. The wye-g/wye-g transformer is the most interesting in this regard.

3 Legged Core Form Transformer
Examine the three legged transformer below. Assume normal conditions exist so that essentially all excitation flux remains in the steel so that negligible excitation flux is passing through air. For this condition the flux in any one leg must equal the flux in the other two legs. Assume that phase A and C primary windings are excited by typical A-N ($1\angle 0$) and C-N ($1\angle 120$) voltages. Note for this analysis, (a) no flux passes through air, (b) $\Phi_A + \Phi_C = -\Phi_B$, and (c) the flux in the A or C legs is defined by the A and C voltages. Therefore the flux in the B phase is fixed and the voltage $V_{B,SEC}$ and $V_{B,PRI}$ must be the same ($\sim 1\angle\text{-}120$) independent of whether the B phase is connected to a voltage source or passively excited from the summation of the A and C core legs. If the transformer were wound wye-g/wye-g (not normally done, as discussed below), it would be difficult to sense phase loss via voltage measurements, even under moderate loading. If such a transformer design had a secondary load, current on the two remaining primary phases would rise and have a major phase

angle swing, but secondary voltage and current would be the normal 1∠0, 1∠-120, and 1∠120. For those wishing to understand this further, the voltage and current conditions will be very similar to those seen in the analysis of the 3x1-phase wye-g/delta transformer, below.

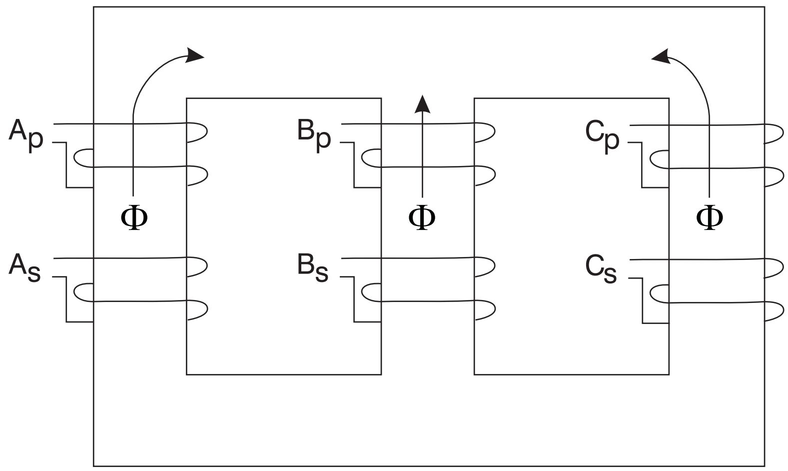


Figure 2: Three Legged Core Transformer

Three legged core transformers are rarely used for wye-g/wye-g transformers. One reason is referred to in the previous paragraph; lost phases will be recreated via a flux balance process with a resultant power flow in directions and paths that were not intended, with a resultant, likely unexpected, overload of phases. Another reason is directly related to the flux balance analysis. If zero sequence voltage or triplen harmonic voltage (triplen=odd multiples of 3; 3rd, 9th, 15th, 21st, ...) is applied to the three windings of a wye-g/wye-g three legged core form transformer, the flux in each core is oriented in the same direction in every leg, and without a separate independent leg in the core for a flux return path, the flux is forced to pass through the transformer oil, air, and tank. The excitation impedance for zero sequence voltages applied to a wye-g/wye-g three legged core transformer is therefore very low (i.e., a very high level of excitation current is required to build up any amount of zero sequence or triplen harmonic voltage on the transformer). The flux flow through the tank can cause transformer damage and ease of saturation by zero sequence voltages can contribute to ferroresonance conditions.

In virtually all 3 legged core form transformers, if there is a wye-g winding there is also a delta winding (e.g., the transformer is wound delta/wye-g or wye-g/wye-g/delta). The delta winding is sometimes referred to as needed for its stabilizing properties. It counters the lack of a zero sequence flux path in the core. If the power source is the delta side, there is no zero sequence flux question since zero sequence flux cannot be created from voltages applied to the delta. If a zero sequence voltage is applied to a wye winding, a zero sequence voltage is induced in the delta and hence a circulating current is generated in the delta. The zero sequence voltages on the wye are in effect shorted out by the delta, and hence minimal zero sequence voltage can be built up on the wye. Any appreciable zero sequence voltage that does build up is then also effectively shorted out by the very low zero sequence excitation impedance of the core form transformer. As seen by the wye-g winding, the combination of shorting the zero sequence voltage by both the delta and the excitation path results in a low zero sequence impedance. On a delta/wye-g transformer typically Z_0 = 0.8-0.95 x Z_1.

4 Legged Core Form Transformer

The 4 legged design is an expansion of the three legged design, as shown below. The 4th leg provides the zero sequence flux path that is missing in the 3 legged core form transformer. This type of transformer core is used in wye-g/wye-g (no delta tertiary) transformers, especially for higher power and higher voltage designs. This design may be readily excited by zero sequence voltages. However, the 4th leg has the same cross section as the main winding legs, so it cannot support all three legs being supplied by full nominal zero sequence voltage. For instance, if all three phases were excited by the same full single phase source voltage, the 4th leg would see 3x as much flux as each winding leg, resulting in the 4th leg saturating. By inspection, one can see that if the thickness of the 4th leg is the same as the phase leg (the normal design) the 4th leg can only support 33% zero sequence voltage in the normal design.

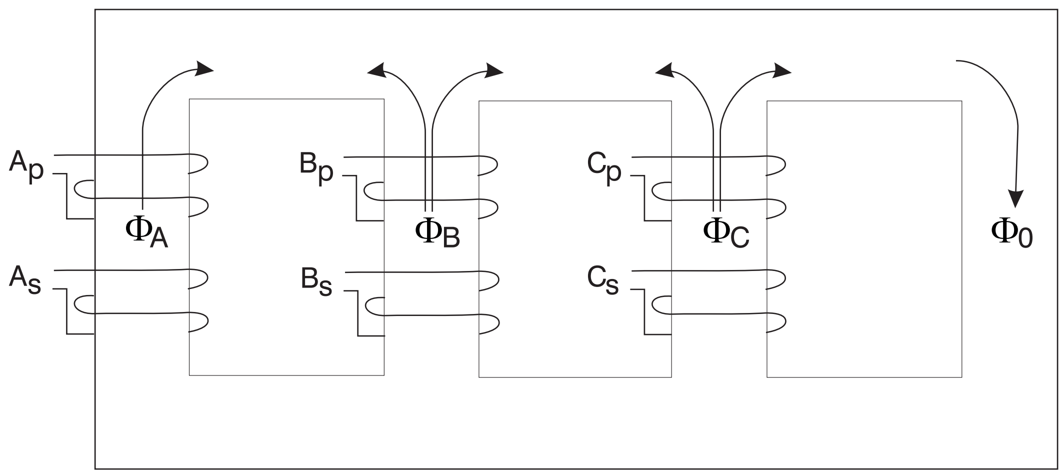


Figure 3: Four-Legged Core Form Transformer

5 Legged Shell Form Transformer

The shell form transformer is representative of a manufacturing process that is optimized for the low cost, lower power (<5MVA) distribution transformer market. In most applications the shell form has the 4 core/5 leg configuration shown in figure 4. Most such transformers are connected wye-g/wye-g but the design is also connected delta/wye-g when such a transformer configuration is ordered (i.e., besides voltage rating and transformer ratio issues, one will receive the same transformer core design independent of whether the transformer is eventually connected delta/wye or wye/wye). The cores in the shell form transformer are wound sheets of steel rather than the stacked sheets of flat steel used in the core form transformer. The coils, especially the low voltage windings, may be flat conductor sheets. For the purposes of phase loss analysis, however, the manufacturing process does not matter. What matters is the flux balance paths available in the core.

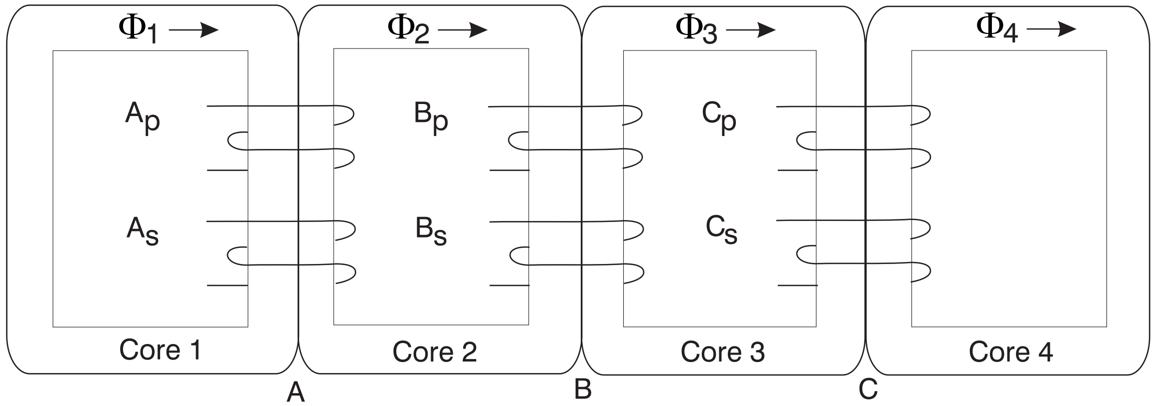


Figure 4: Five-Legged Shell Form Transformer

The results of a phase loss change substantially depending on which phase is lost. As one example of what occurs, consider energizing the transformer only from the A phase. About half the excitation flux of phase A, Φ_A, will be in core 1, and half in core 2. Core 2 couples to the B phase winding, so that the B phase winding is energized at $-0.5V_A$ and the C winding sees no flux at all. If the B phase carries even a tiny amount of load, the V_B falls till I_B is on the order of excitation current, and the current will couple flux to core 3 and now the C phase will be excited at $-0.5V_A$.

In this transformer there are 4 cores that need to be analyzed simultaneously to understand flux conditions in the transformer. Each winding of the transformer excites two cores, and for two cases, the core is excited by two windings. The equations that relate current to flux include:

$$\begin{aligned} \Phi_1 &= -k_1 I_A \\ \Phi_2 &= k_1(I_A - I_B) \\ \Phi_3 &= k_1(I_B - I_C) \\ \Phi_4 &= k_1 I_C \\ \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 &= 0 \end{aligned} \qquad \text{Eq. 2}$$

In the equations above, Φ is flux and I is total effective phase current, primary minus secondary, including accounting for the turns ratio (the difference is the excitation current). The first four equations and the associated k_1 are simplified linearized approximations of the steel's non-linear excitation characteristics. While not highly accurate, it is close enough for the intent of this analysis, as long as saturation is not reached. The fifth equation simply is the summation of the first 4 equations and is to be used in conjunction with the voltage equations below to find a unique solution to the flux state for a given set of voltages.

The equations that relate flux to winding voltages are:

$$\begin{aligned} V_A &= k_2(-\Phi_1 + \Phi_2) \\ V_B &= k_2(-\Phi_2 + \Phi_3) \\ V_C &= k_2(-\Phi_3 + \Phi_4) \end{aligned} \qquad \text{Eq. 3}$$

In the equation above k_2 includes a proportionality constant and a 'd/dt' operation, since voltage is a derivative of flux. From equation 2, $\Phi_1+\Phi_2+\Phi_3+\Phi_4 = 0$. If the sum of Φ is 0, then the sum of the time derivatives of Φ is 0. Therefore:

$$\frac{d}{dt}\Phi_1+\frac{d}{dt}\Phi_2+\frac{d}{dt}\Phi_3+\frac{d}{dt}\Phi_4=0 \qquad \text{Eq. 4}$$

These equations can be re-worked to find a set of equations that can be solved for flux given an applied voltage:

$$\begin{vmatrix} V_A \\ V_B \\ V_C \\ 0 \end{vmatrix} = k_2 \begin{vmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{vmatrix} \cdot \begin{vmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \Phi_4 \end{vmatrix} \qquad \text{Eq. 5}$$

If a winding were open circuited (i.e., lost) the equations will change. Open circuited should be read to mean a total disconnect of both the primary and secondary winding from loads or voltage sources. When open circuited, a coil cannot carry current so the coupling that the coil provides between its associated cores is removed. The coupling is removed because in this transformer core design, the core-core magnetic coupling is actually an electrical current effect: one core induces a voltage in the coil it shares with the next-door core, hence as long at there is a current path, it induces a current in the shared coil. This current in turn magnetizes the next core. Beside leakage flux across the core-core gap and current flow in a common coil, there is no core-core coupling.

It is left to the reader to re-think through the equations to see how they change when a coil is open circuited. This was done for the analysis to follow and in Reference 2, and it may become apparent with some study of the following tables that the result of a phase loss is not intuitive.

Summing every equation in Eq. 3, and noting the definition for V_0 from equation 1, it can be seen that $3V_0 = k_2(-\Phi_1+\Phi_4)$. Therefore it can be seen that the two outer cores of the transformer constitute the zero sequence flux path of the transformer. On a transformer energized by a wye-g winding, $\Phi_1 = \Phi_4$ only when $V_0 = 0$. On a transformer connected delta and excited from the delta connection, $V_0 = 0$ to the transformer, so Φ_1 is always equal to Φ_4.

PHASE LOSS ANALYSIS

The analysis of the system in Figure 1 starts at the low voltage distribution level. In order to review the most basic transformer first, the analysis starts with phase loss with the wye-g/wye-g 3x1-phase transformer. This transformer is found predominantly in the power system at the step down to the final customer, so the analysis to follow is effectively beginning at the customer end of the power system and working back upstream toward the main distribution substation and the associated transmission system. While the wye-g/wye-g is the predominant end-customer three phase distribution level transformer, there are some utilities and end customers that use delta/wye-g transformers, especially at the larger MVA

(2+) level when they wish to isolate the grounding systems of the end customer from the utility. The delta/wye-g transformer is frequently not preferred for use at the end customer level because of an increased susceptibility of the transformer (compared to the wye-g/wye-g transformer) to enter into ferroresonance and the reduced ability of fuses on the primary to protect the transformer from faults on the secondary.

Wye-G / Wye-G Transformer Bank

Analysis - 3x1-Phase, One or Two Phases Lost, No Back-Feed from Load
For this configuration the transformer effect is a simple voltage and current ratio change from primary to secondary.

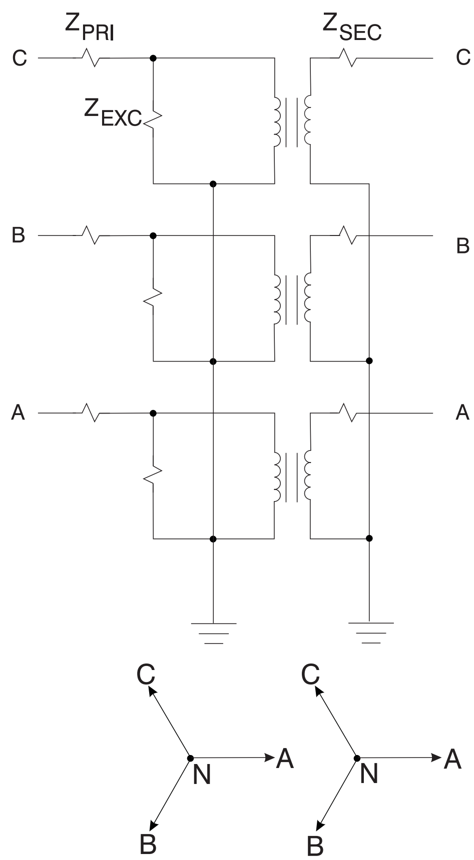


Figure 5: Wye-Wye Transformer

As long as loads do not back-feed the lost phase(s), the loss of a phase means the phase's voltage is pulled to zero through the loads and the transformer excitation paths, so determining the voltages after the phase loss is a simple application of the transformer ratio and sequence component theory. Under the loss of one or two phases of the source the following voltages will be measured at the transformer terminals:

Table 4

Wye-G/Wye-G, 3x1 Xfmr; no load back-feed; primary and secondary voltages					
B phase lost (Figure 6a)					
V_{AN}	1.000∠0	$V_{AB,}$	1.000∠0 (/√3=0.577)	$V_{0,LN}$	0.333∠60
V_{BN}	0	V_{BC}	1.000∠-60 (/√3=0.577)	$V_{1,LN}$	0.667∠0
V_{CN}	1.000∠120	V_{CA}	1.732∠150 (/√3=1.00)	$V_{2,LN}$	0.333∠-60
B and C phase lost (Figure 6b)					
V_{AN}	1.000∠0	V_{AB}	1.000∠0 (/√3=0.577)	$V_{0,LN}$	0.333∠0
V_{BN}	0	V_{BC}	0	$V_{1,LN}$	0.333∠0
V_{CN}	0	V_{CA}	1.000∠180 (/√3=0.577)	$V_{2,LN}$	0.333∠0

Analysis - 3x1-Phase, One or Two Phases Lost, Substantial Phase to Phase Back-Feed from Load

A problem with the system described by Table 4 occurs under conditions where $V_{BN}=0$ and/or $V_{CN}=0$, but there is minimal phase to neutral loading to stabilize and hold $V_{BN,CN}=0$. In such cases the phases are only weakly connected to neutral through the excitation impedance of the B and C phase transformers. Table 4 holds as long as secondary loads do not provide a path for one phase to back-feed onto another. One path for a load to back-feed into a lost phase is if the loads are connected phase to phase, as might be the case for nearby delta/wye transformers. Three phase motor backfeed will be considered later. For VT secondary circuits, a sneak phase to phase load might be a phase to phase connected relay, and another sneak feedback path would be an auxiliary VT connected in a wye-g to broken delta arrangement (see later section on wye-delta transformers). If any phase to phase load is connected to the lost phase, a path is introduced in the circuit to reverse excite the lost phase through the load impedance. In the example V_{BN} (and V_{CN}) is pulled from 0V. If one phase is lost and there are only phase-phase connected loads, the lost phase will be pulled to roughly the midpoint of the remaining two phases, as shown in Table 6 and Figure 6d. If two phases are lost, any phase to phase loads will tend to cause all three phases to pull together, as shown in Table 8 and Figure 6e. The following table reflects the voltages that will be sensed:

Table 5

Wye-G/Wye-G, 3x1 Xfmr, ph-ph load back-feed to lost phase; primary and secondary voltages					
B phase lost (Figure 6d)					
V_{AN}	1∠0	V_{AB}	~0.866∠-30 (/√3=0.50)	$V_{0,LN}$	0.500∠60
V_{BN}	~0.5∠60	V_{BC}	~0.866∠-30 (/√3=0.50)	$V_{1,LN}$	0.500∠0
V_{CN}	1∠120	V_{CA}	1.732∠150 (/√3=1.00)	$V_{2,LN}$	0.500∠-60
B and C phase lost (Figure 6e)					
V_{AN}	1∠0	V_{AB}	~0	$V_{0,LN}$	~1∠0
V_{BN}	~1∠0	V_{BC}	~0	$V_{1,LN}$	0
V_{CN}	~1∠0	V_{CA}	~0	$V_{2,LN}$	0

Analysis - 3x1-Phase, B to C Fault with Only C Fuse Operation

Closely associated with the loss of one or two phases is the condition where there is a permanent B to C fault. The first fuse to operate clears the fault from the perspective of the source. Assume that only the C phase fuse operates and now both B and C phases are energized with the phase B potential. The condition will be represented by the following table.

Table 6

Wye-G/Wye-G, 3x1 Xfmr; primary and secondary voltages					
B to C Fault, C fuse operates (Figure 6c)					
V_{AN}	1.000∠0	V_{AB}	1.732∠30 (/√3=1.000)	$V_{0,LN}$	0.577∠-90
V_{BN}	1.000∠-120	V_{BC}	0	$V_{1,LN}$	0.577∠30
V_{CN}	1.000∠-120	V_{CA}	1.732∠90 (/√3=1.000)	$V_{2,LN}$	0.577∠30

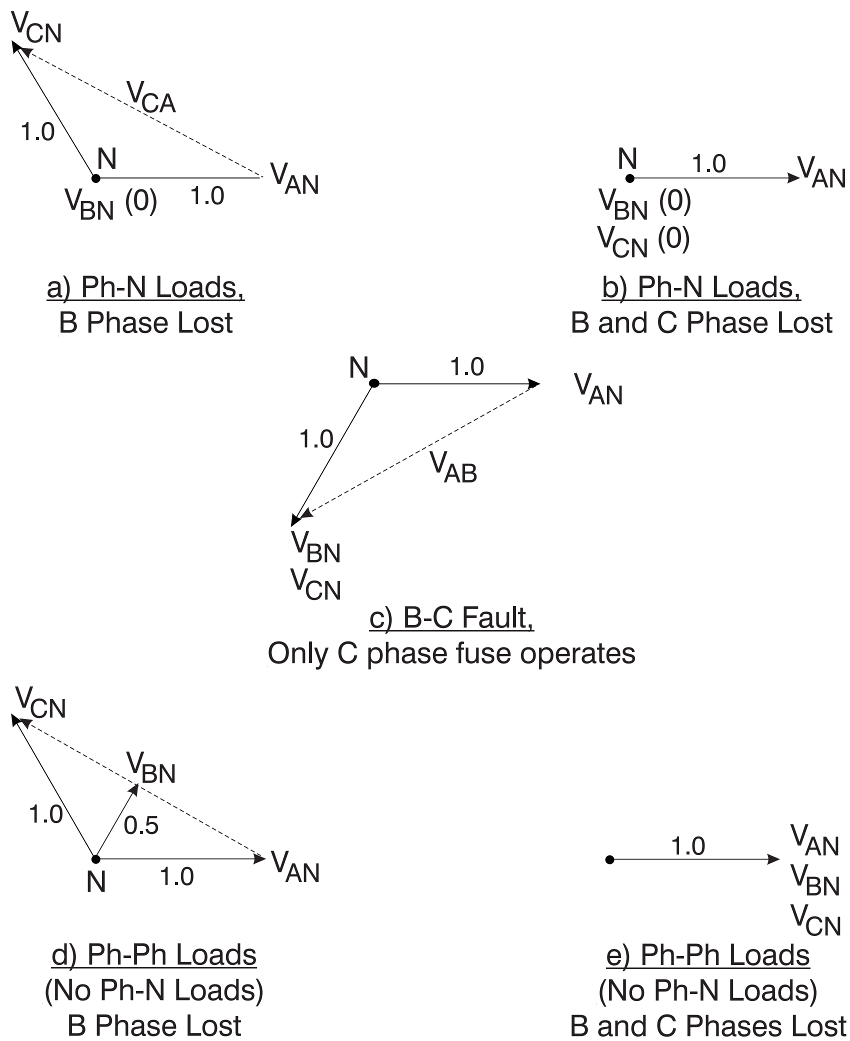


Figure 6: Y-Y 3x1-ph Voltage Phasors

If there is a mix of phase to phase and phase to neutral loads or if the phase to phase load loading is light so that the tendency of the load connections to pull the lost phase from neutral does not overpower the tendency of the excitation branch and phase to neutral loads to pull the lost phase to neutral, then Tables 4 and 5 together approximate what occurs. A detailed equivalent circuit and set of equations would be required to determine the final voltages, but such an effort may be an impractical and low productivity process. The important thing to note is that if the loads are connected phase to phase, and one or two phases are lost on the primary, the voltages may not be zero on the lost phases. It is possible when two phases are lost that negligible negative sequence voltage will be developed, so the 47 relay may be ineffective. By including a 27_{LL} or a 59N the loss of the source is still detected.

Analysis - 4 Legged Core Form, One or Two Phases Lost, No Back-Feed from Load
The 4-legged core form transformer reacts the nearly same as the 3x1-phase transformer bank, as described in Table 4, except the core has the possibility of excitation of lost phases under a no load condition. Examine Figure 3. Note that if only phase A, for instance, is excited, the flux associated with phase A excitation has three paths to take: through the B coil, the C coil, or the zero sequence flux leg. As long as no load is attached

to the B or C legs, the flux will follow the path of least reluctance and, hence, some energization of the B and C windings will result. However, if any load at all is pulled (especially if it will attempt to pull current equal to or greater than the excitation current of phase A), the flux in that leg will be reduced and the zero sequence flux leg will start to carry the phase A flux instead. Hence if there are any phase to neutral loads on the primary or secondary of the lost phase, the voltages on the lost phases will fall to 0 and the system will appear more like Table 4.

Analysis - 4-Legged Core Form, One or Two Phases Lost, Substantial Phase to Phase Back-Feed from Load

The 4-legged core form transformer, when loaded phase to phase, will try to act similar to the 3x1-phase bank, Table 5, but examination of Table 5 indicates again that this condition will tend to cause large zero sequence voltages at the transformer. Again, this will tend to cause the transformer's zero sequence flux leg to saturate due to the transformer's 0.333pu zero sequence voltage limit. Note that the lost phase voltages of Table 5 reflect voltage reaching the transformer excitation branch via the high impedance of the loads. If saturation does occur in the zero sequence flux leg, zero sequence excitation currents will increase, the excitation branch impedance falls, and the voltages V_{BN} and V_{CN} in Table 5 are pulled back toward 0 and a balance between V_0, I_0, and Z_0 is reached. Hence, V_{BN} and V_{CN} in Table 5 are high by an unclear amount, but V_0 and V_2 should still be sufficient to be detected as an improper condition and hence initiate tripping.

Analysis - 4-Legged Core Form, B to C Fault with Only C Fuse Operation

The 4-legged core form transformer for this condition will try to act similar to the 3x1-phase bank, Table 6, but examination of Table 6 indicates the zero sequence voltage that will arise for this condition is beyond the capability of the zero sequence leg of the transformer to carry flux. Recall from earlier analysis, that the 4th leg (the zero sequence flux leg) in standard design can carry the flux associated with 0.333pu zero sequence voltage on the phases. The zero sequence leg in this 'B-C/C fuse only operation' condition will seriously saturate. The transformer will start to pull large zero sequence currents that may be detected by overcurrent devices. Since the transformer will not be operating in the linear region, harmonic content of the current will be high. The voltage levels indicated in Table 6 will not be met due to voltage drops associated with the large current flow, but V_2 should still be sufficient to be detected as an improper condition and hence initiate tripping.

Analysis, 5-Legged Shell Form, One or Two Phases Lost, No Back-Feed from Load

The 'no back-feed from load' condition needs to be broken down into two parts for complete analysis. As described under the theory of the shell form transformer, there is different flux distribution depending on whether a lost phase is completely open (no loads connected at all) and when even a small load is placed on the transformer.

In the open circuit condition, the voltages induced on opened phases have minimal current carrying capability. As soon as current is carried in a load on that phase, the primary/source winding sees less back emf, and in accordance with transformer action, more current is delivered to build flux back up. However, in this transformer design, the source excites two cores, not just the one with the load. The flux in the second core rises with the increased current in the source winding, which increases back emf in the source winding.

So instead of increasing current in the source winding, the load on the lost phase has shifted flux to the second core and this in turn blocks the transformer from supplying any more load current to the lost phase than the increase in excitation current in the source winding. The effect under open phase condition will vary depending on whether the middle B phase is opened or whether one of the outside A or C phases are opened.

In Table 7 the condition with completely open circuit is given. In Table 8, the situation with a small amount of load is shown.

Table 7

Wye-G/Wye-G, 5 Legged Shell Form Xfmr, completely opened phase(s) (No load), primary and secondary voltages					
B phase lost (middle phase)					
V_{AN}	1.00∠0	V_{AB}	~1.32∠19.1 (/√3=0.764)	$V_{0,LN}$	0.167∠60
V_{BN}	~0.5∠-120	V_{BC}	~1.32∠-79.1(/√3=0.764)	$V_{1,LN}$	0.833∠30
V_{CN}	1.00∠120	V_{CA}	1.732∠150(/√3=1.000)	$V_{2,LN}$	0.167∠-60
C phase lost (outside phase)					
V_{AN}	1.00∠0	V_{AB}	1.732∠30 (/√3=1.0)	$V_{0,LN}$	0.193∠-30
V_{BN}	1.00∠-120	V_{BC}	1.53∠-109 (/√3=0.882)	$V_{1,LN}$	0.839∠-6.6
V_{CN}	0.577∠90	V_{CA}	1.15∠150 (/√3=0.666)	$V_{2,LN}$	0.193∠90
A and C phase lost (two outside phases)					
V_{AN}	0.5∠60	V_{AB}	1.50∠60 (/√3=0.866)	$V_{0,LN}$	0
V_{BN}	1∠-120	V_{BC}	1.50∠-120 (/√3=0.866)	$V_{1,LN}$	0.866∠30
V_{CN}	0.5∠60	V_{CA}	0	$V_{2,LN}$	0.866∠90
B and C phase lost (middle + one outside phase)					
V_{AN}	1.0∠0	V_{AB}	1.50∠0 (/√3=0.866)	$V_{0,LN}$	0.167∠0
V_{BN}	0.5∠180	V_{BC}	0.50∠180 (/√3=0.289)	$V_{1,LN}$	0.441∠-19.1
V_{CN}	0	V_{CA}	1.00∠180 (/√3=0.577)	$V_{2,LN}$	0.441∠19.1

Table 8, next, shows the same conditions under a small load. It is un-interesting in that there is no unusual phase to phase coupling occurring and the voltages have returned to collapsing to zero for the lost phases. This might be of importance in an automatic transfer scheme monitoring for the return of the source. The voltages in Table 7 could initiate a re-transfer of load, but as soon as load is applied, the voltage collapses.

Table 8

Wye-G/Wye-G, 5 Legged Shell Form Xfmr, opened phase(s), with some Ph-N loading					
B phase lost (middle phase)					
V_{AN}	1.00∠0	V_{AB}	1.732∠30	$V_{0,LN}$	0.333∠-60
V_{BN}	~0	V_{BC}	1.00∠-120	$V_{1,LN}$	0.667∠0
V_{CN}	1.00∠120	V_{CA}	1.00∠180	$V_{2,LN}$	0.333∠60
C phase lost (outside phase)					
V_{AN}	1.00∠0	V_{AB}	1.732∠30	$V_{0,LN}$	0.333∠-60
V_{BN}	1.00∠-120	V_{BC}	1.00∠-120	$V_{1,LN}$	0.667∠0
V_{CN}	~0	V_{CA}	1.00∠180	$V_{2,LN}$	0.333∠60
A and C phase lost (two outside phases)					
V_{AN}	~0	V_{AB}	1.0∠60	$V_{0,LN}$	0.333∠-120
V_{BN}	1∠0	V_{BC}	1.0∠-120	$V_{1,LN}$	0.333∠0
V_{CN}	~0	V_{CA}	0	$V_{2,LN}$	0.333∠120
B and C phase lost (middle + one outside phase)					
V_{AN}	1.00∠0	V_{AB}	1.0∠0	$V_{0,LN}$	0.333∠0
V_{BN}	~0	V_{BC}	0	$V_{1,LN}$	0.333∠0
V_{CN}	~0	V_{CA}	1.0∠180	$V_{2,LN}$	0.333∠0

Analysis - 5-Legged Shell Form, One or Two Phases Lost, Substantial Phase to Phase Back-Feed from Load

The 5-legged shell form transformer, when loaded phase to phase, will try to act similar to the 3x1-phase bank, Table 5, but application of Equation 5 shows that the condition will try to over-excite the cores. However, just as for the 4-legged core form transformer, the phases are only weakly pulled to the overexcitation condition through the high impedances of the loads. As soon as the overexcitation condition arises, the excitation branch impedance falls, and the voltages V_{BN} and V_{CN} in Table 6 are pulled back toward 0 and a balance between V_0, I_0, and Z_0 is reached. Hence, V_{BN} and V_{CN} in Table 5 are high by an unclear amount for this situation but V_0 and V_2 should still be sufficient to be detected as an improper condition and, hence, initiate tripping.

Analysis - 5-Legged Shell Form, B to C Fault with Only C Fuse Operation

The 5-legged shell form transformer for this condition will try to act similar to the 3x1-phase bank, Table 6, but application of Equation 5 shows that the condition will try to severely overexcite the core (Figure 7d). High current levels will arise that may be detected by overcurrent devices. Since the transformer will not be operating in the linear region, harmonic content of the current will be high. The voltage levels indicated in Table 6 will not be met due to voltage drops associated with the large current flow. Due to the high saturation level it is hard to predict system conditions and to what level the sequence components of Table 6 will be seen.

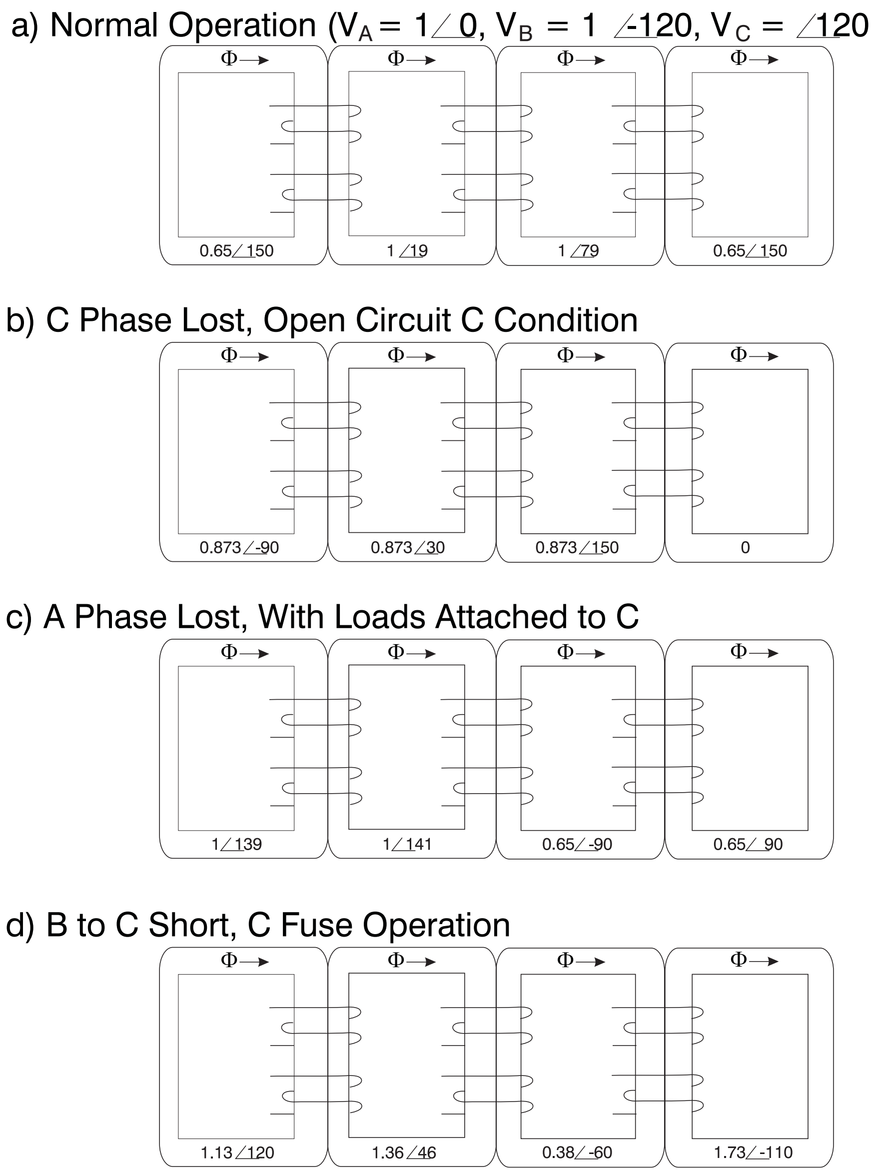


Figure 7 - Flux Balance in Core Form Transformer

Detection

A comparison of Tables 2 and 3 and Tables 4 through 8 reveals a 47 and 59N set to 10-15% of V_2 and V_0 will sense single phasing conditions for a wye-g/wye-g transformer configuration on a grounded system. If a 27_{LL} or 27_{LN} is used, the 27 may need supervision by a "27-3 out of 3" block logic to prevent operation during a total station outage. In all applications, a time delay will need to be added to the functions to prevent the system from declaring a single phase condition during a load switching operation or fault condition that temporarily causes a degraded or unbalanced voltages. If a minimum load can be guaranteed, a 50U (undercurrent) element will provide a means of sensing phase loss also.

The risk of saturation is greater for a 4-legged core form and 5-legged shell form transformer than for the 3x1 phase bank during a phase-phase fault with operation of one phase's fuse, or with a phase loss in conjunction with a high level of phase-phase loads. For these transformers, overcurrent relaying or high I_2 detection may sense the saturation condition.

Verification of Predictions

As verification of the predictions, 3 single-phase modeling transformers were configured wye-g/wye-g and wired as shown in Appendix 1. Test voltages were applied and monitored with a metering device. Predicted values from tables 4-8 were compared with measured test values in the following tables. One per unit phase to neutral voltage was 27.3Vac. The corresponding nominal V_{LL} is 47.8Vac:

Table 9

Test Data, predicted vs. measured								
Wye-G/Wye-G, 3x1 Xfmr, B phase primary lost, ph-n loads only								
V_{AN}	$1.000\angle 0$	$27.2\angle 0$	V_{AB}	$1.000\angle 0$	$27.3\angle 0$	$V_{0,LN}$	$0.333\angle 60$	$9.08\angle 60.2$
V_{BN}	0	0	V_{BC}	$1.000\angle -60$	$27.3\angle -60$	$V_{1,LN}$	$0.667\angle 0$	$18.17\angle 0$
V_{CN}	$1.000\angle 120$	$27.3\angle 120.3$	V_{CA}	$1.732\angle 150$	$47.3\angle 150$	$V_{2,LN}$	$0.333\angle -60$	$9.08\angle -60.2$
Wye-G/Wye-G, 3x1 Xfmr, B and C phase primary lost, ph-n loads only								
V_{AN}	$1.000\angle 0$	$27.2\angle 0$	V_{AB}	$1.000\angle 0$	$27.3\angle 0$	$V_{0,LN}$	$0.333\angle 0$	$9.07\angle 0$
V_{BN}	0	0	V_{BC}	0	0	$V_{1,LN}$	$0.333\angle 0$	$9.07\angle 0$
V_{CN}	0	0	V_{CA}	$1.000\angle 180$	$27.3\angle 180$	$V_{2,LN}$	$0.333\angle 0$	$9.07\angle 0$
Wye-G/Wye-G, 3x1 Xfmr, B phase primary lost, ph-ph loads								
V_{AN}	$1\angle 0$	$25.7\angle 0$	V_{AB}	$0.866\angle -30$	$23.4\angle -30$	$V_{0,LN}$	$0.500\angle 60$	$13.4\angle 62.0$
V_{BN}	$\sim 0.5\angle 60$	$12.4\angle 65$	V_{BC}	$0.866\angle -30$	$21.7\angle -30$	$V_{1,LN}$	$0.500\angle 0$	$13.5\angle -3.9$
V_{CN}	$1\angle 120$	$27.1\angle 116.5$	V_{CA}	$1.732\angle 150$	$44.9\angle 150$	$V_{2,LN}$	$0.500\angle -60$	$12.44\angle -61.4$
Wye-G/Wye-G, 3x1 Xfmr, B & C phase primary lost, ph-ph loads only								
V_{AN}	$1\angle 0$	$27.5\angle 0$	V_{AB}	~0	~6.9	$V_{0,LN}$	$\sim 1\angle 0$	$24.07\angle 6.5$
V_{BN}	$\sim 1\angle 0$	$22.4\angle 10.6$	V_{BC}	~0	~0.2	$V_{1,LN}$	0	$2.27\angle -38.8$
V_{CN}	$\sim 1\angle 0$	$22.6\angle 10.3$	V_{CA}	~0	~6.7	$V_{2,LN}$	0	$2.23\angle -35.6$

There is some disagreement between predicted vs. measured data in Table 9 that is attributable to the high excitation currents of the test transformers.

DELTA / WYE-G TRANSFORMER BANK

Analysis - General Considerations, Normal Operating Conditions

This configuration refers to a transformer energized from the delta winding, with loads on the wye. In most applications the delta winding will be the higher voltage winding and, hence, referred to as the transformer primary. The transformer effect is complicated by the interconnection of the phase voltages on the delta side.

In the delta/wye-g transformer, the core construction has low impact on the phase loss condition. The 3x1phase transformer, the 3- or 4-legged core form transformer, and the 5-legged shell form transformer will react approximately the same under phase loss condition. The method by which flux in one phase induces a voltage on the two other phases is the same as the effect of the delta. Consider the DAB delta/wye-g transformer in Figure 8 (DAB means the delta A phase is connected to the transformer A polarity and B non-polarity). If V_{AB} is applied to a delta winding, and V_C is left floating, the voltage V_{AB} would tend to divide evenly between V_{BC} and V_{CA} in accordance with the voltage divider rule. The same thing would occur with the core flux in a three legged core form transformer. The flux generated by the A leg excitation would tend to divide evenly between the B and C legs. If this were a 4 legged core form transformer or a 5 legged shell form transformer, the flux would have an alternate path of the zero sequence flux paths, but the voltage division of the delta winding would tend to force a division of A leg flux between the B and C legs.

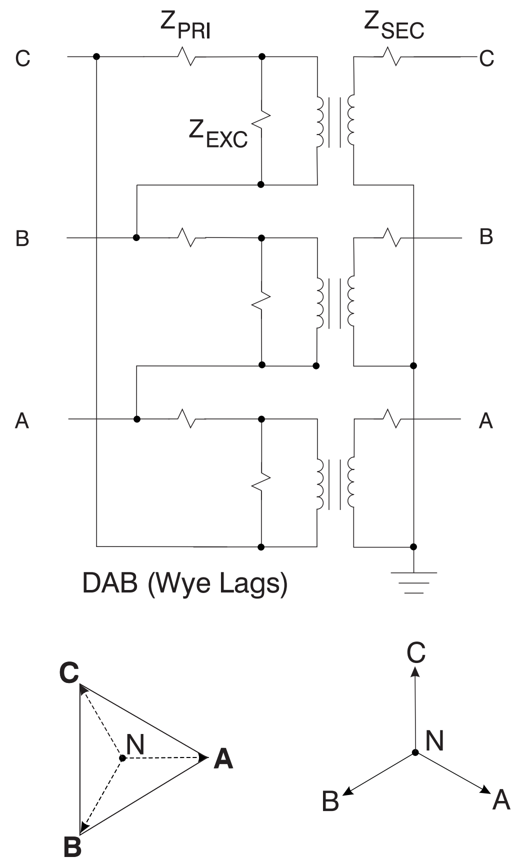


Figure 8: DAB Transformer

In sequence component analysis, with a DAB connected primary, the secondary positive sequence phase voltage will lag the primary by 30 degrees, and the secondary negative sequence phase voltage will lead the primary by 30 degrees. Zero sequence voltage on the primary is blocked by the delta winding and cannot be transferred to the secondary. Assuming the phase voltage unbalances described in Table 2, it might be informative to apply these concepts to examine how the delta/wye transformer will affect the voltages measured on the secondary. After the affect of the transformer connections on the sequence components, the voltages sensed on the secondary will be:

Table 10

Delta/Wye-G Xfmr, Example system V_{LN} unbalance (Table 2), transferred to secondary; Secondary (Wye) Voltages					
V_{AN}	1.040∠-29.3	V_{AB}	1.784∠-1.6 (/√3=1.030)	$V_{0,LN}$	0
V_{BN}	0.989∠-152.3	V_{BC}	1.659∠-120.6 (/√3=0.958)	$V_{1,LN}$	0.999∠-29.9
V_{CN}	0.969∠91.9	V_{CA}	1.750∠122.4 (/√3=1.010)	$V_{2,LN}$	0.043∠-14.1

The phase to neutral and phase to phase per unit voltages are affected by the transformer, but there is no change in the magnitude of V_1 or V_2 from one side of the transformer to the other.

Analysis - One Phase Lost

Upon the loss of, for example, phase B, the only remaining normal voltage at the transformer is the V_{CA} voltage. Due to the B phase being connected via the delta connection to the A and C phases, the B phase voltage will not drop to zero. Voltages V_{AB} and V_{CB} become a series network so that $V_{AB}+V_{BC} = V_{CA}$. A voltage divider principle will be needed to determine specific V_{AB}, V_{BC}, and V_{BN} voltages. For instance:

$$V_{BN} = V_{CA}\left(\frac{Z_{AB}}{Z_{AB}+Z_{BC}}\right) \qquad \text{Eq. 6}$$

where Z_{AB} and Z_{BC} are the equivalent impedances of the transformer excitation impedance, transformer through current impedances, and load impedances as indicated in Figure 9. In the simple analysis of Figure 9, all secondary loads are phase-neutral connected, but if phase to phase loads exist, the voltage on one phase back-feeds to another, and the matter becomes a three phase simultaneous analysis.

Trying to determine the exact voltage that will result is likely a low value effort. The important things to know is the range of voltages that are feasible during an event and then to be ready with appropriate relay settings. To obtain a better picture of the voltages that will arise during the loss of a phase, assume two sets of voltages that might feasibly arise:

case 1) $V_{AB,PRI} = V_{BC,PRI} = -0.5^* V_{CA,PRI}$, and
case 2) $V_{AB,PRI} = -0.3^* V_{CA}$; $V_{BC,PRI} = -0.7^* V_{CA,PRI}$. This is a rough approximation of A-C load impedance being 1/2 the B-C load impedance.

These voltages can be seen in Tables 11 and 12 and Figure 10. It might be interesting to note $V_{BN,PRI}$ downstream of the phase loss location will not be 0 and will instead be an unusual voltage from neutral to a point on the V_{CA} phasor, best described by investigating Figure 10.

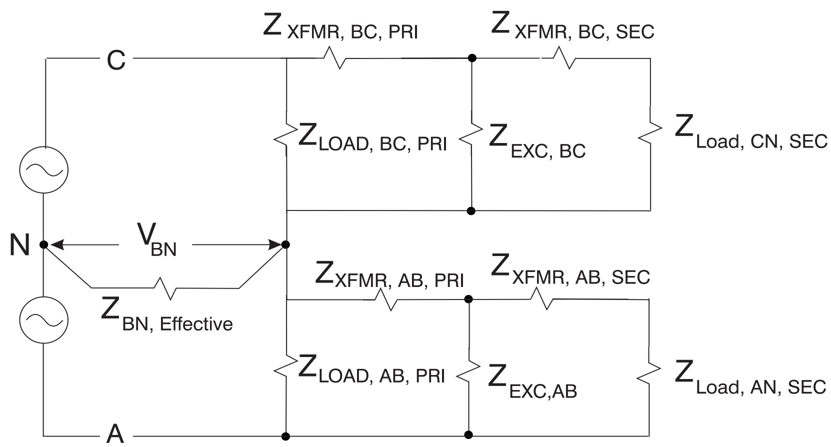


Figure 9: B Phase Voltage Circuit

Table 11

Delta/Wye-G Xfmr, B phase lost, $V_{AB,PRI} = -0.5*V_{CA,PRI}$; $V_{BC,PRI} = -0.5*V_{CA,PRI}$					
Primary (Delta) Voltages (Figure 10a)					
V_{AN}	1.000∠0	V_{AB}	0.866∠-30 (/√3=0.500)	$V_{0,LN}$	0.500∠60.0
V_{BN}	0.500∠60	V_{BC}	0.866∠-30 (/√3=0.500)	$V_{1,LN}$	0.500∠0.0
V_{CN}	1.000∠120	V_{CA}	1.732∠150 (/√3=1.000)	$V_{2,LN}$	0.500∠-60
Secondary (Wye) Voltages (Figure 10b)					
V_{AN}	1.000∠-30	V_{AB}	1.500∠-30 (√3=0.866)	$V_{0,LN}$	0
V_{BN}	0.500∠150	V_{BC}	0	$V_{1,LN}$	0.500∠-30
V_{CN}	0.500∠150	V_{CA}	1.5∠150 (/√3=0.866)	$V_{2,LN}$	0.500∠-30

Table 12

Delta/Wye-G Xfmr, B Phase lost, $V_{AB,PRI} = -0.7*V_{CA,PRI}$; $V_{BC,PRI} = -0.3*V_{CA,PRI}$					
Primary (Delta) Voltages (Figure 10c)					
V_{AN}	1.000∠0.0	V_{AB}	1.212∠-30 (/√3=0.700)	$V_{0,LN}$	0.513∠73.0
V_{BN}	0.608∠94.7	V_{BC}	0.520∠-30 (/√3=0.300)	$V_{1,LN}$	0.513∠-13.0
V_{CN}	1.000∠120.0	V_{CA}	1.732∠150 (/√3=1.000)	$V_{2,LN}$	0.513∠-47.0
Secondary (Wye) Voltages (Figure 10d)					
V_{AN}	1.000∠-30.0	V_{AB}	1.700∠-30 (/√3=0.981)	$V_{0,LN}$	0
V_{BN}	0.700∠150.0	V_{BC}	0.4∠150 (/√3=0.231)	$V_{1,LN}$	0.513∠-43.0
V_{CN}	0.300∠150.0	V_{CA}	1.3∠150 (/√3=0.751)	$V_{2,LN}$	0.513∠-17.0

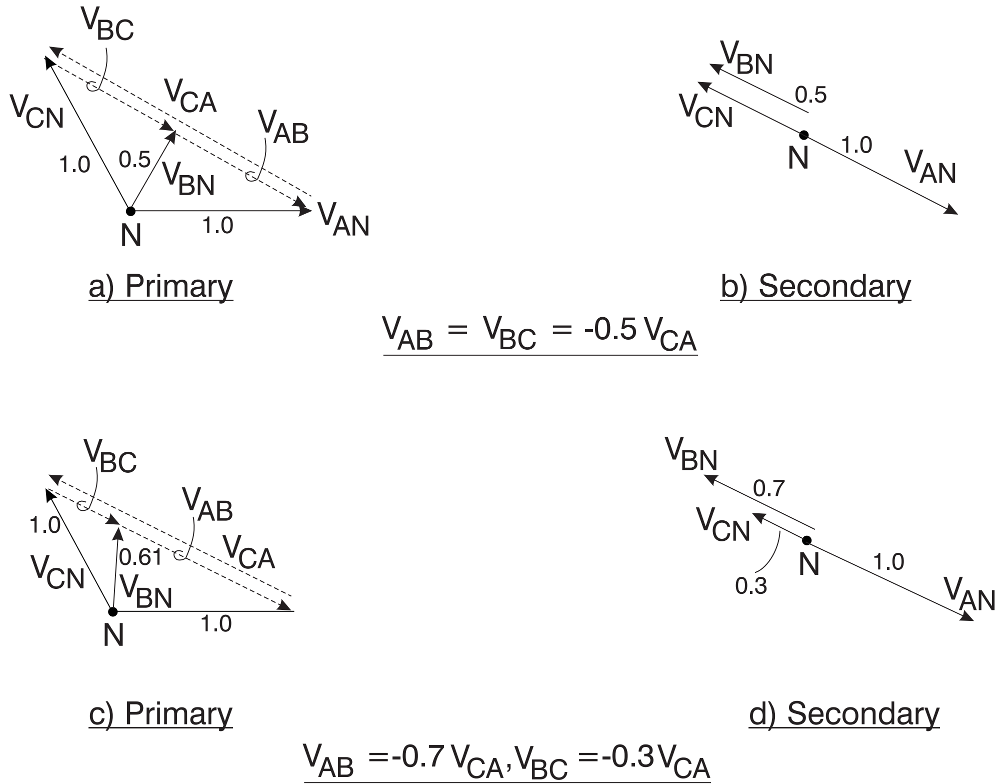


Figure 10: Delta Wye Transformer Voltage Phasors with One Phase Lost

Analysis - Two Phases Lost

For many applications, loss of two phases on the delta primary results in a complete secondary station outage. However, one needs to analyze what has occurred on the lost phases before concluding the transformer secondary has truly become de-energized.

If there are no loads or only phase to phase loads on the primary an inspection of the load paths and transformer excitation paths will reveal that the phase to neutral voltage on the two lost phases will be effectively shorted (through a high impedance path) to the remaining good phase. A device measuring the voltage on the primary will find all three phases having the same potential, so a large apparent zero sequence primary voltage is set up on the primary. The delta connection cannot pass zero sequence voltage, so the secondary remains de-energized.

However, if there are substantial primary phase to neutral loads, or if there is a standing phase-phase-neutral fault on the two lost phases, these two phases will be pulled to ground, which results in a voltage across two of the transformer primaries. The voltage seen across the primary will involve a voltage divider rule between the primary load and the secondary load referred to the primary. The secondary will now see a voltage, but likely a very low voltage. Refer to the following tables and Figure 11 for analysis.

Table 13

Delta/Wye-G Xfmr, B and C phase lost, no phase to neutral primary loads					
Primary (Delta) Voltages (Figure 11a)					
V_{AN}	1.000∠0	V_{AB}	0	$V_{0,LN}$	1∠0
V_{BN}	~1∠0	V_{BC}	0	$V_{1,LN}$	0
V_{CN}	~1∠0	V_{CA}	0	$V_{2,LN}$	0
Secondary (Wye) Voltages (Figure 11b)					
V_{AN}	0	V_{AB}	0	$V_{0,LN}$	0
V_{BN}	0	V_{BC}	0	$V_{1,LN}$	0
V_{CN}	0	V_{CA}	0	$V_{2,LN}$	0

Table 14

Delta/Wye-G Xfmr, B and C phase lost, phase-neutral primary and secondary load approximately the same					
Primary (Delta) Voltages (Figure 11c)					
V_{AN}	1.000∠0	V_{AB}	~0.5∠0 (/√3=0.289)	$V_{0,LN}$	0.667∠0
V_{BN}	~0.5∠0	V_{BC}	~0	$V_{1,LN}$	0.167∠0
V_{CN}	~0.5∠0	V_{CA}	~0.5∠180 (/√3=0.289)	$V_{2,LN}$	0.167∠0
Secondary (Wye) Voltages (Figure 11d)					
V_{AN}	0.289∠0	V_{AB}	0.577∠0 (/√3=0.333)	$V_{0,LN}$	0
V_{BN}	0.289∠180	V_{BC}	0.289∠180 (/√3=0.167)	$V_{1,LN}$	0.167∠-30
V_{CN}	~0	V_{CA}	0.289∠180 (/√3=0.167)	$V_{2,LN}$	0.167∠30

Table 15

Delta/Wye-G transformer, B and C phase lost, primary phase-neutral load >> than secondary phase-neutral load, or a standing primary B-C-neutral fault.					
Primary (Delta) Voltages (Figure 11e)					
V_{AN}	1.000∠0	V_{AB}	~1∠0 (/√3=0.577)	$V_{0,LN}$	0.333∠0
V_{BN}	~0	V_{BC}	~0	$V_{1,LN}$	0.333∠0
V_{CN}	~0	V_{CA}	~1∠180 (/√3=0.577)	$V_{2,LN}$	0.333∠0
Secondary (Wye) Voltages (Figure 11f)					
V_{AN}	0.577∠0	V_{AB}	1.155∠0 (/√3=0.667)	$V_{0,LN}$	0
V_{BN}	0.577∠180	V_{BC}	0.577∠180 (/√3=0.333)	$V_{1,LN}$	0.333∠-30
V_{CN}	~0	V_{CA}	0.577∠180 (/√3=0.333)	$V_{2,LN}$	0.333∠30

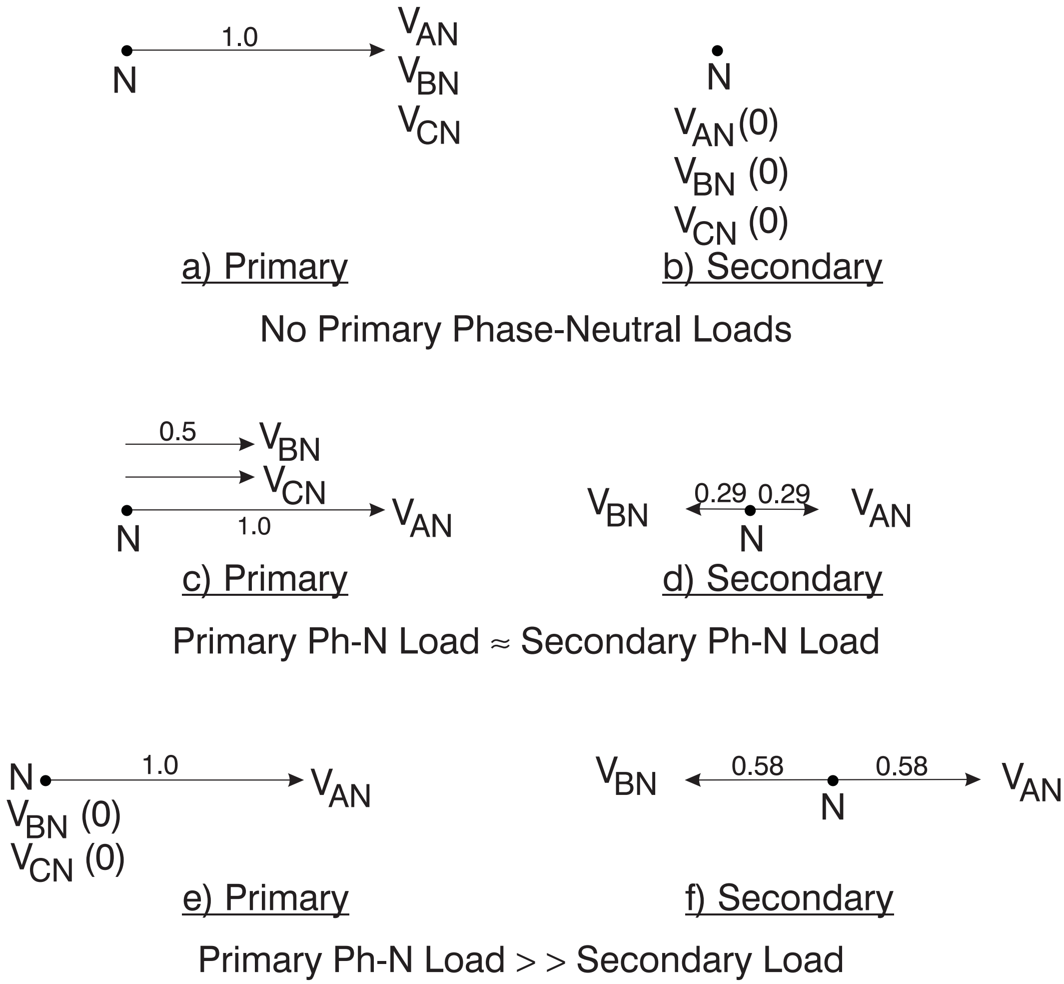


Figure 11: Delta-Wye Phasors, B and C Phases Lost

Analysis - B to C Fault with Only C Fuse Operation

Closely associated with the loss of one or two phases is the condition where there is a permanent B to C fault. The first fuse to operate clears the fault from the perspective of the source. Assume that only the C phase fuse operates so now both B and C phases are energized with the phase B potential. This condition classifies as a phase loss. The condition will be represented by the following table:

Table 16

Delta/Wye-G transformer, B to C Fault, only C phase fuse trips Primary (Delta) Voltages (Figure 12a)					
V_{AN}	1.000∠0	V_{AB}	~1.732∠30 (/√3=1.00)	$V_{0,LN}$	0.577∠-90
V_{BN}	1.000∠-120	V_{BC}	~0	$V_{1,LN}$	0.577∠30
V_{CN}	1.000∠-120	V_{CA}	~1.732∠150 (/√3=1.00)	$V_{2,LN}$	0.577∠30
Secondary (Wye) Voltages (Figure 12b)					
V_{AN}	1.00∠30	V_{AB}	2.00∠30 (/√3=1.155)	$V_{0,LN}$	0
V_{BN}	1.00∠-150	V_{BC}	1.00∠-150 (/√3=0.577)	$V_{1,LN}$	0.577∠0
V_{CN}	0	V_{CA}	1.00∠-150 (/√3=0.577)	$V_{2,LN}$	0.577∠60

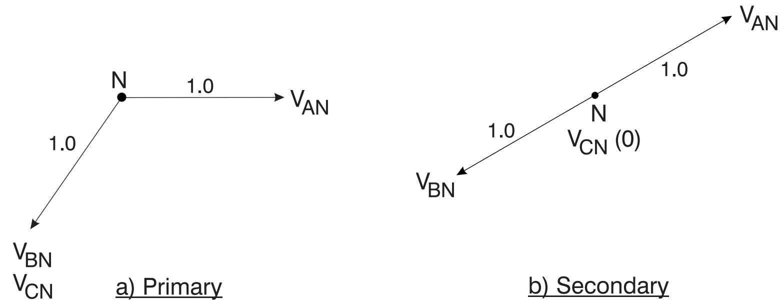


Figure 12: Delta-Wye Phasors, B to C Fault, Only C Phase Fuse Trips

Analysis - 3 Wire Ungrounded System

It was mentioned at the start that weakly grounded and ungrounded systems would not be closely analyzed and would be left to the reader to reason through using concepts developed in this paper for grounded systems. However, it might be noted that the loss of a phase to a delta closely resembles fuse loss on an ungrounded system. If the source had been an ungrounded 3 wire source, the effect of the loss of one phase or two phases will be very similar to the 4 wire grounded system except that the effects of phase to neutral loads will not exist.

Detection

Compare Tables 2, 3, and 10, to Tables 11 through 16. It can be seen that there is a range for which a 27(l-l or l-n) or a 47 device on the transformer secondary will trip for the loss of one or two phases and not trip for normal system unbalances. If monitoring on the primary voltages, the conditions described in table 13 would require a 27_{LL} or a 59N relay. As previously mentioned, the 27 may need supervision by a “27, 3 out of 3” block logic to prevent operation during a total station outage, and of course time delay will need to be added to the functions to prevent the system from declaring a single phase condition during a downstream fault condition that temporarily causes a degraded voltages.

Verification of Predictions

As verification of the predictions, 3 single-phase modeling transformers (Appendix 1) were configured delta/wye-g and wired as shown inAppendix 1. Test voltages were applied and monitored with a metering device. Predicted values were compared with measured test values for both the primary and secondary windings. One PU primary V_{LN} voltage=69.3Vac, and the corresponding nominal V_{LL}was120Vac. One PU secondary V_{LN} =27.2Vac. The corresponding nominal V_{LL} = 47.2Vac.

Table 17

Test Data, Delta/Wye-G, 3x1 Xfmr, B phase lost, $Z_{AB} = Z_{BC}$, Predicted vs. Measured								
Primary (Delta) Voltages								
V_{AN}	1.000∠0	69.3∠0	V_{AB}	0.866∠-30	59∠-30	$V_{0,LN}$	0.500∠60	34.1∠59.9
V_{BN}	0.500∠60	34.0∠58.6	V_{BC}	0.866∠-30	61∠-30	$V_{1,LN}$	0.500∠0.0	34.9∠1.1
V_{CN}	1.000∠120	69.3∠121	V_{CA}	1.732∠150	120∠150	$V_{2,LN}$	0.500∠-60	34.8∠-60.1
Secondary (Wye) Voltages								
V_{AN}	1.000∠-30	27.2∠-30	V_{AB}	1.500∠-30	40.7∠-30	$V_{0,LN}$	0	0
V_{BN}	0.500∠150	13.4∠149.2	V_{BC}	0	0.6	$V_{1,LN}$	0.500∠-30	13.6∠-29.4
V_{CN}	0.500∠150	13.9∠150.4	V_{CA}	1.5∠150	41.2∠150.3	$V_{2,LN}$	0.500∠-30	13.6∠-30.6

For the unbalance voltage test ($Z_{AB} = 2 \times Z_{BC}$), one PU secondary line-neutral voltages were V_{AN}= 27.3, V_{BN}=27.3, V_{CN}=26.5. The corresponding nominal line-line voltages were V_{AB}=47.1, V_{BC}=46.8, V_{CA}=46.4. One PU primary V_{LN} was 69.3Vac balanced, and the corresponding nominal V_{LL} was 120Vac balanced.

Table 18

Test Data, 3x1-phase Delta/Wye-G Xfmr, B phase lost, load: $Z_{AB} = 2 \times Z_{BC}$, Predicted vs. Measured								
Primary (Delta) Voltages								
V_{AN}	1.000∠0.0	69.3Ð0.0	V_{AB}	1.212∠-30	76.5∠-30.0	$V_{0,LN}$	0.513∠73.0	34.5∠69.5
V_{BN}	0.608∠94.7	37.3∠86.3	V_{BC}	0.520∠-30	43.5∠-31.6	$V_{1,LN}$	0.513∠-13.0	35.5∠-8.5
V_{CN}	1.000∠120.0	69.4∠120.7	V_{CA}	1.732∠150	120∠149.6	$V_{2,LN}$	0.513∠-47.0	34.8∠-50.7
Secondary (Wye) Voltages								
V_{AN}	1.000∠-30.0	27.3∠-30.0	V_{AB}	1.700∠-30	44.6∠-30	$V_{0,LN}$	0	0
V_{BN}	0.700∠150.0	17.4∠150.9	V_{BC}	0.4∠150	7.8∠154	$V_{1,LN}$	0.513∠-43.0	14.0∠-39.4
V_{CN}	0.300∠150.0	9.6∠147.6	V_{CA}	1.3∠150	36.9∠149.5	$V_{2,LN}$	0.513∠-17.0	13.6∠-20.5

Next, a 3-phase core form (3-legged) modeling transformer (Appendix 1) was configured delta/wye-g with the source connected to the delta (primary) and load connected to the wye (secondary) as shown in Appendix 1. Test voltages were applied and monitored with a metering device. Predicted values were compared with measured test values for both the primary and secondary windings. One PU primary (delta side) V_{LN}=20.0Vac, and the corresponding V_{LL}=34.7Vac. One PU secondary (wye side) V_{LN} =66.4Vac, and the corresponding V_{LL}=115Vac:

Table 19

Test Data, Delta/Wye-G, Three Legged Core Form Xfmr, B Phase lost, $Z_{AB} = Z_{BC}$, Predicted vs. Measured								
Primary Voltages								
V_{AN}	1.000∠0	20.0∠0	V_{AB}	0.866∠-30	18.1∠-30	$V_{0,LN}$	0.500∠60	10∠61.5
V_{BN}	0.500∠60	10.2∠64.4	V_{BC}	0.866∠-30	16.6∠-30	$V_{1,LN}$	0.500∠0.0	10.1∠-1.4
V_{CN}	1.000∠120	20.1∠120.1	V_{CA}	1.732∠150	34.7∠150	$V_{2,LN}$	0.500∠-60	10.1∠-58.5
Secondary Voltages								
V_{AN}	1.000∠-30	66.7∠-30	V_{AB}	1.500∠-30	101.0∠-30	$V_{0,LN}$	0	0.4
V_{BN}	0.500∠150	34.9∠149.9	V_{BC}	0	3.0	$V_{1,LN}$	0.500∠-30	33.2∠-31.3
V_{CN}	0.500∠150	31.9∠150.8	V_{CA}	1.5∠150	98.6∠150	$V_{2,LN}$	0.500∠-30	33.5∠-28.4

WYE-G / DELTA TRANSFORMER BANK

Analysis - General Considerations, Normal Operating Conditions

This configuration refers to the wye-g/delta transformer excited from the wye side, independent of which side is the high voltage side. This configuration will arise in grounding bank applications, in distributed generation (DG) applications, and in substation back-feed conditions.

This transformer configuration may be applicable to the DG that is back-feeding the power system through a delta-wye distribution transformer, so that the wye side becomes the source side rather than the load side. This could apply either local to the DG at plant level voltages with the DG back-feeding a medium voltage distribution line, or back at the utility substation where the distribution line to which the DG is connected now back-feeds the bulk transmission system. If the transformer was in a back-feed situation and a phase was lost, a complete analysis would investigate the situation of the delta being energized simultaneously, but since analysis of conditions with dual sources is not being addressed in this paper, the material below will address the simplified situation of exciting the transformer from the wye side and the delta side being a pure load. It is acknowledged that this is a double contingency situation, but it is included for completeness of the transformer effects topic.

In a grounding bank application there is usually no load on the secondary. If the delta is completed with no impedance, the delta effectively short circuits any zero sequence voltages and prevents the wye connected phases from developing an offset from ground. Another application of wye/delta transformers is to place an impedance in the delta and monitor voltage across the impedance; the voltage measured will be proportionate to quantity $3I_0$. The circuit is the voltage equivalent of summing 3 phase CTs to measure $3I_0$. There will be difficulties in regards to broken delta transformers on VT circuits; they can force a reproduction of a lost phase during a phase loss condition, described below.

Just as for the delta/wye-g transformer, the core construction will play a reduced role relative to the wye-g/wye-g transformer since the delta blocks zero sequence flux buildup and since the delta performs electrically the same effects as core flux sharing.

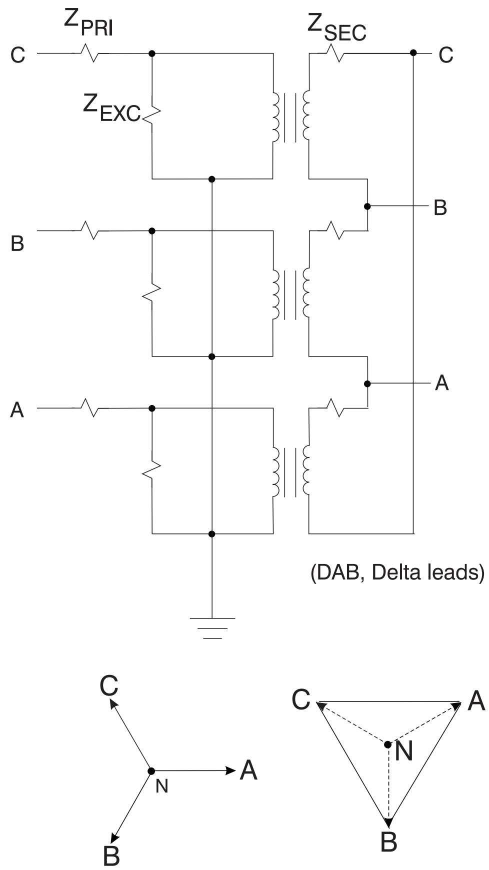


Figure 13: Wye Delta Transformer

Analysis - One Phase Lost, Voltage Recreation

If one phase is lost on the wye source, the lost phase is recreated on the wye by back-feed from the delta. For instance, assume the B phase source on the wye side is lost in figure 13. Since in the delta $V_{AB}=V_{BC}+V_{CA}$ and since $V_{AN,PRI}$ and $V_{CN,PRI}$ are not affected by the loss of B phase, then a voltage is induced in the secondary and $V_{AB,SEC}$ and hence $V_{BN,PRI}$ is virtually completely recreated.

Under normal operating conditions, summing the voltage in the delta loop, $V_A + V_B + V_C = 0$. The positive and negative sequence components in the delta loop always sum to zero. However, if any zero sequence voltage is applied, a circulating current equal to $V_{0,Xfmr}/Z_{Xfmr}$ starts to flow and V_0 is shorted. However, if for instance, B phase is lost, summing the voltage around the delta loop shows:

$$V_B = -[V_A + V_C]$$

Recall that:

$$\begin{vmatrix} V_A \\ V_B \\ V_C \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{vmatrix} \cdot \begin{vmatrix} V_0 \\ V_1 \\ V_2 \end{vmatrix}$$

Therefore measuring at the transformer wye terminals (downstream of the phase loss), using the sequence components found on the other side of the phase loss point (upstream of the phase loss) we will find a B phase voltage:

$$\begin{aligned} V_{B,Wye} &= -\left[2V_0 + (1+a)V_1 + (1+a^2)V_2\right] \\ &= -2V_0 + (1\angle -120)V_1 + (1\angle +120)V_2 \end{aligned} \qquad \text{Eq. 7}$$

Inspection of equation 7 shows that as long as the voltage feeding the remaining A and C phase is representative of a normal power system where V_0 and V_2 are low and V_1 is normal, a relatively normal voltage is seen at phase B. Downstream of the phase loss there is no unusual V_2 and no V_0 at all (the delta back-feed V_{BN} described above can be seen to be equal and opposite V_0 in V_{AN} and V_{CN}), so there is no easy detection of this condition with voltage sensing elements.

Table 20

Wye-G/Delta Xfmr, B phase primary (Wye) lost Source (Wye) voltages (Figure 14a)					
V_{AN}	1.00∠0	V_{AB}	~1.732∠30 (/√3=1)	$V_{0,LN}$	0
V_{BN}	~1.0∠-120	V_{BC}	~1.732∠-90 (/√3=1)	$V_{1,LN}$	~1∠0
V_{CN}	1.00∠120	V_{CA}	1.732∠150 (/√3=1)	$V_{2,LN}$	~0
Delta Voltages (Figure 14b) (Delta leads)					
V_{AN}	1.00∠30	V_{AB}	~1.732∠60	$V_{0,LN}$	0
V_{BN}	1.00∠-90	V_{BC}	1.732∠-60	$V_{1,LN}$	~1∠30
V_{CN}	1.00∠150	V_{CA}	1.732∠180$V_{2,LN}$	~0	

Analysis - One Phase Lost, Loaded Delta

Just as for the unloaded delta applications, if a single phase is lost in the wye source the phase to neutral voltage of the lost phase will be fairly well reproduced via the delta winding feed-back process. The voltages in table 20 still apply, assuming voltage drop problems associated with unbalanced primary side load flow do not become too severe.

Because the loss of a single phase will be very difficult to sense with voltage elements, it may necessary to monitor currents. Since the B phase transformer cannot deliver any current, the A and C phases must carry additional current, the result will be a high level of current unbalance on the primary side of the transformer. To better see what will occur, examine the load currents that will arise when phase B is lost in a case where the transformer and system impedance is low relative to the load impedance:

Table 21

Wye-G/Delta, Xfmr, B phase primary (Wye) lost, with secondary (Delta) load							
Relative currents before phase B is lost, 1.0 power factor (currents in phase with voltage). Secondary currents on the lines outside the delta							
$I_{A,PRI}$	$1.00\angle 0$	$I_{0,PRI}$	0	$I_{A,SEC}$	$1.00\angle 30$	$I_{0,SEC}$	0
$I_{B,PRI}$	$1.00\angle -120$	$I_{1,PRI}$	$1.00\angle 0$	$I_{B,SEC}$	$1.00\angle -90$	$I_{1,SEC}$	$1.00\angle 30$
$I_{C,PRII}$	$1.00\angle 120$	$I_{2,PRI}$	0	$I_{C,SEC}$	$1.00\angle 150$	$I_{2,SEC}$	0
Relative currents after phase B is lost (Figure 14c, 14d)							
$I_{A,PRI}$	$1.732\angle 30$	$I_{0,PRI}$	$1.0\angle 60$	$I_{A,SEC}$	$1.00\angle 30$	$I_{0,SEC}$	0
$I_{B,PRI}$	0	$I_{1,PRI}$	$1.0\angle 0$	$I_{B,SEC}$	$1.00\angle -90$	$I_{1,SEC}$	$1.00\angle 30$
$I_{C,PRI}$	$1.732\angle 90$	$I_{2,PRI}$	~0	$I_{C,SEC}$	$1.00\angle 150$	$I_{2,SEC}$	0

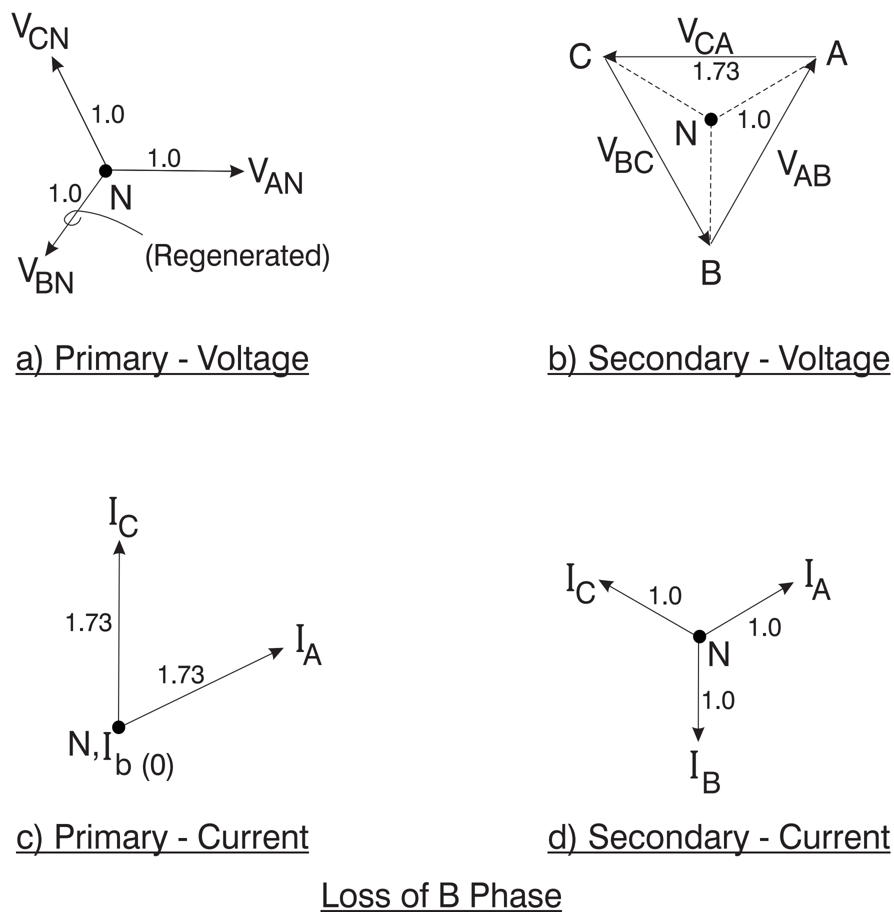


Figure 14: Wye Delta Phasors with One Phase Lost

The current conditions after the loss of a single phase of the source may be hard to see intuitively. Note the lack of negative sequence current in the transformer. Note the phase relationship between currents and voltages in the wye. Note the large amounts of zero sequence current in the wye, even though the phase B transformer in the delta carries no current (and hence the classical concept of zero sequence current circulating in the delta does not seem to work well here). An intuitive “by inspection” understanding of the currents may be seen by this reasoning process:

(a) Since it was already shown the B voltage has been fairly well recreated, assume the load sees only positive sequence currents where the delta leads (in this example) the wye by 30^0, so $I_A=1\angle 30$, $I_B=1\angle -90$, $I_C=1\angle 150$.

(b) Note that for a 1:1 wye/delta transformer the actual turns ratio is √3, so that if examining the currents inside the delta, one finds $I_{WYE\ SIDE} = 1.732*I_{DELTA\ SIDE}$.

(c) Note that $I_{B,XFMR} = 0$.

(d) Examination of figure 13 will show for $I_{B,XFMR} = 0$, then $I_{A,LINE\ TO\ LOAD} = I_{A,XFMR,\ DELTA\ SIDE}$, and $I_{B,LINE\ TO\ LOAD} = -I_{C,XFMR,\ DELTA\ SIDE}$.

The reader should now be able to use this data to carry the logic forward and see $I_{A,B,C,WYE\ SIDE}$ by inspection.

Analysis - Two Phases Lost

If two phases are lost on the wye source, the remaining source will develop a voltage in the delta that will be split between the two lost phases and back-fed into the wye windings. If for example the B and C voltages are lost, the voltages V_{AB} and V_{BC} is an application of a voltage divider network and is dependent on the relative loading of the two phases. If loading is approximately equal, then $V_{AB} \sim V_{BC}$.

Table 22

Wye-G / Delta, Xfmr B and C Phase lost, assuming $V_{BN} = V_{CN}$					
Primary Voltages (Figure 15a)					
V_{AN}	1.000∠0	V_{AB}	1.5∠0 (/√3=0.866)	$V_{0,LN}$	0.500∠0
V_{BN}	~0.5∠180	V_{BC}	~0	$V_{1,LN}$	0.500∠0.0
V_{CN}	~0.5∠180	V_{CA}	1.5∠180 (/√3=.866)	$V_{2,LN}$	0.500∠0
Secondary Voltages (Figure 15b)					
V_{AN}	0.866∠0	V_{AB}	0.866∠-0 (/√3=0.500)	$V_{0,LN}$	0
V_{BN}	0	V_{BC}	0.866∠0 (/√3=0.500)	$V_{1,LN}$	0.500∠30
V_{CN}	0.866∠180	V_{CA}	1.732∠180 (/√3=1.000)	$V_{2,LN}$	0.500∠-30

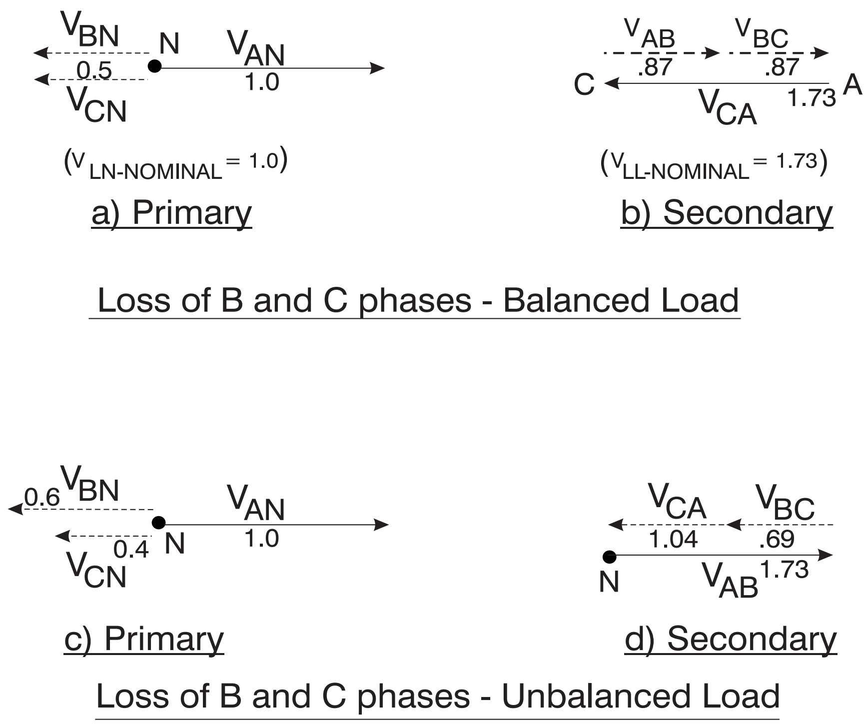


Figure 15: Wye-G / Delta Phasors with Two Phases Lost

Detection

For this transformer configuration, for the loss of a single phase on the wye source, detection will be difficult with voltage elements. Downstream of the phase loss there is no unusual V_2 and no V_0 at all. If this is a grounding bank that is expected to carry measurable current regularly, one option is to alarm for an undercurrent condition that exist for an excessive period of time. Another option in some limited applications where a known possible phase loss point can be accessed is to monitor for I_0 and V_0 upstream of the fuse loss point. If V_0 exists without I_0, there is a strong indication of a phase loss. If load exists on the delta winding, the loss of a phase will be marked by high zero sequence current, one phase falling to 0, and high current on the remaining phases. This may provide the signature to indicate a phase loss condition.

The loss of two phases causes low phase voltages and high levels of V_0 and V_2. The condition is easily recognized by voltage functions 27, 47, and 59N.

Verification of Predictions

As verification of the predictions, 3 single-phase modeling transformers were configured delta/wye-g with the source connected to the wye (secondary) and load connected to the delta (primary) as shown in Appendix 1. Effectively, this test was for a wye-g/delta step-up transformer connection. Test voltages were applied and monitored with a metering device. Predicted values were compared with measured test values for both the primary and secondary windings. One PU secondary (wye side) V_{LN} =19.7Vac, and the corresponding nominal V_{LL}=34.0Vac and phase current=1.58amps. One PU primary (delta side) V_{LN}=43.9Vac, and the corresponding V_{LL}=76.0Vac, and nominal I_{LINE}=0.61amps. The transformer was heavily overloaded to the level of simulating a cross between normal overloads and fault conditions.

Table 23

Test Data, Wye-G/Delta (step-up), 3x1-phase Xfmr, B Phase lost on Wye side (source), Predicted vs. Measured								
Secondary (wye side) Voltages, Currents								
V_{AN}	1.00∠0	19.9∠0	I_A	1.73∠30	2.32∠10.9	I_0	1.0∠60	1.13∠51.28
V_{BN}	~1∠-120	14.0∠-127	I_B	0	0	I_1	1.0∠0.0	1.43∠-7.18
V_{CN}	1.00∠120	19.7∠122.4	I_C	1.73∠90	2.22∠93.9	I_2	~0	0.2
Primary (delta side) Voltages, Currents								
V_{AN}	1.00∠30	35.1∠28	I_A	1.00∠30	0.54∠26.3	I_0	0	0
V_{BN}	1.00∠-90	40.6∠-81.1	I_B	1.00∠-90	0.50∠-79	I_1	1∠30	0.55∠30
V_{CN}	1.00∠150	43.0∠148.4	I_C	1.00∠150	0.61∠156.1	I_2	~0	0.073

Error between predicted and measured is attributable to relatively high transformer excitation current.

Next, a 3-phase core form (3-legged) modeling transformer (Appendix 1) was configured delta/wye-g with the source connected to the wye (secondary) and load connected to the delta (primary) as shown in Appendix 1. Effectively, this test was for a wye-g/delta step-up transformer connection. Test voltages were applied and monitored with a metering device. Predicted values were compared with measured test values for both the primary and secondary windings. One PU secondary (wye side) V_{LN}=100Vac, and the associated nominal V_{LL} was 173.0Vac and nominal I_{LINE} was0.28amps. One PU primary (delta side) V_{LN} was 103.0Vac, and the associated nominal V_{LL}=178.0Vac, and nominal I_{LINE} was 0.20amps.

Table 24

Test Data, Wye-G/Delta (step-up), Three Legged Core Form Xfmr, B Phase lost on Wye side (source), Predicted vs. Measured								
Secondary (wye side) Voltages, Currents								
V_{AN}	1.00∠0	99.9∠0	I_A	1.73∠30	.38∠21.1	I_0	1.0∠60	0.21∠59.8
V_{BN}	~1∠-120	64.7∠-125	I_B	0	0.0	I_1	1.0∠0.0	0.24∠-0.4
V_{CN}	1.00∠120	100∠120.4	I_C	1.73∠90	.38∠98.1	I_2	~0	0
Primary (delta side) Voltages, Currents								
V_{AN}	1.00∠30	85.6∠30	I_A	1.00∠30	0.21∠29.6	I_0	0	0
V_{BN}	1.00∠-90	82.0∠-74.4	I_B	1.00∠-90	0.19∠-70.4	I_1	1∠30	0.21∠40.6
V_{CN}	1.00∠150	102.9∠160.2	I_C	1.00∠150	0.24∠163.1	I_2	~0	0

DELTA / DELTA TRANSFORMER BANK

Analysis - General Considerations, Normal Operating Conditions

This type of transformer configuration is not common in most power systems, partly due to the lack of a ground reference on either winding. However, in systems that are deliberately isolated from ground, the configuration does arise. It is also included for completeness of coverage of the topic. For this bank, the core construction under normal conditions will have minimal effect on the phase loss analysis.

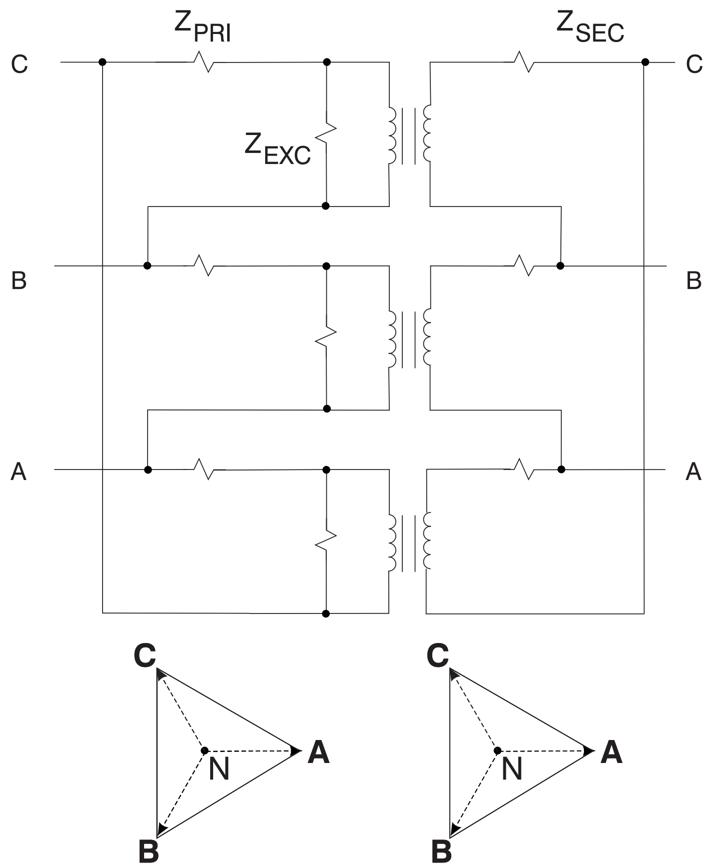


Figure 16: Delta-Delta Transformer

Under the loss of one phase, this transformer will behave very similarly to the delta-wye transformer previously analyzed. However, in a delta-delta transformer, there is likely no phase to neutral load, and the transformer is more likely to be part of a 3 wire ungrounded source, so the effect of phase to neutral loads can be ignored and it will be assumed that a two phase fuse loss will completely de-energize the secondary.

One Phase Lost

Upon the loss of, for example, phase B, the only remaining normal voltage at the transformer is the V_{CA} voltage. Due to the B phase being connected via the delta connection to the A and C phases, the B phase voltage to will not drop to zero, but will be forced to some level on the voltage phasor V_{CA}. Voltages V_{AB} and V_{CB} become a series network so that $V_{AB}+V_{CB} = V_{CA}$. A voltage divider principle as previously discussed with the delta/wye connection will be needed to determine specific V_{AB}, V_{CB}, and V_{BN} voltages.

The table below represents one possible voltage division. While in the delta-delta transformer there is no reference to neutral, it is assumed that the power system as a whole will still have a neutral reference so phase to neutral voltages are referred to in this table. The delta/delta connection isolates this primary ground reference from the secondary, so the secondary phase to neutral voltages differ from the primary.

Table 25

Delta-Delta, Xfmr B Phase lost, Assuming $V_{AB,PRI} = V_{BC,PRI} = -0.5 * V_{CA,PRI}$					
Primary Voltages (Figure 17a)					
V_{AN}	1.000∠0	V_{AB}	0.866∠-30 (/√3=0.500)	$V_{0,LN}$	0.500∠60.0
V_{BN}	0.500∠60	V_{BC}	0.866∠-30 (/√3=0.500)	$V_{1,LN}$	0.500∠0.0
V_{CN}	1.000∠120	V_{CA}	1.732∠150 (/√3=1.000)	$V_{2,LN}$	0.500∠-60
Secondary Voltages (Figure 17b)					
V_{AN}	0.866∠-30	V_{AB}	0.866∠-30 (/√3=0.500)	$V_{0,LN}$	0
V_{BN}	0	V_{BC}	0.866∠-30 (/√3=0.500)	$V_{1,LN}$	0.500∠0.0
V_{CN}	0.866∠150	V_{CA}	1.732∠150 (/√3=1.000)	$V_{2,LN}$	0.500∠-60

Two Phases Lost

If two phases are lost, the excitation branches of the transformer and any phase to phase loads on the primary will tend to pull all phases together and the transformers will appear to be energized by a zero sequence source. No voltage will be transferred to the secondary.

Table 26

Delta-Delta Xfmr, B and C Phase lost					
Primary Voltages					
V_{AN}	1.000∠0	V_{AB}	0	$V_{0,LN}$	1∠0
V_{BN}	~1∠0	V_{BC}	0	$V_{1,LN}$	0
V_{CN}	~1∠0	V_{CA}	0	$V_{2,LN}$	0
Secondary Voltages					
V_{AN}	0	V_{AB}	0	$V_{0,LN}$	0
V_{BN}	0	V_{BC}	0	$V_{1,LN}$	0
V_{CN}	0	V_{CA}	0	$V_{2,LN}$	0

Figure 17: Delta/Delta Transformer Voltage Phasors, B Phase Lost

Detection

For this transformer configuration, the loss of a single phase on the delta source can be detected with a 27_{LL} or 47 function. The loss of two phases could be detected with a 27_{LL} function.

OPEN-DELTA / OPEN-DELTA 2X1-PHASE TRANSFORMER BANK

Analysis - General Considerations, Normal Operating Conditions

This type of transformer configuration is used mainly for a more economical instrument voltage transformers for phase to phase voltage detection (rather than a 3x1-phase arrangement for phase to neutral voltages). This arrangement is used in some utilities for an economical 3 phase power transformer.

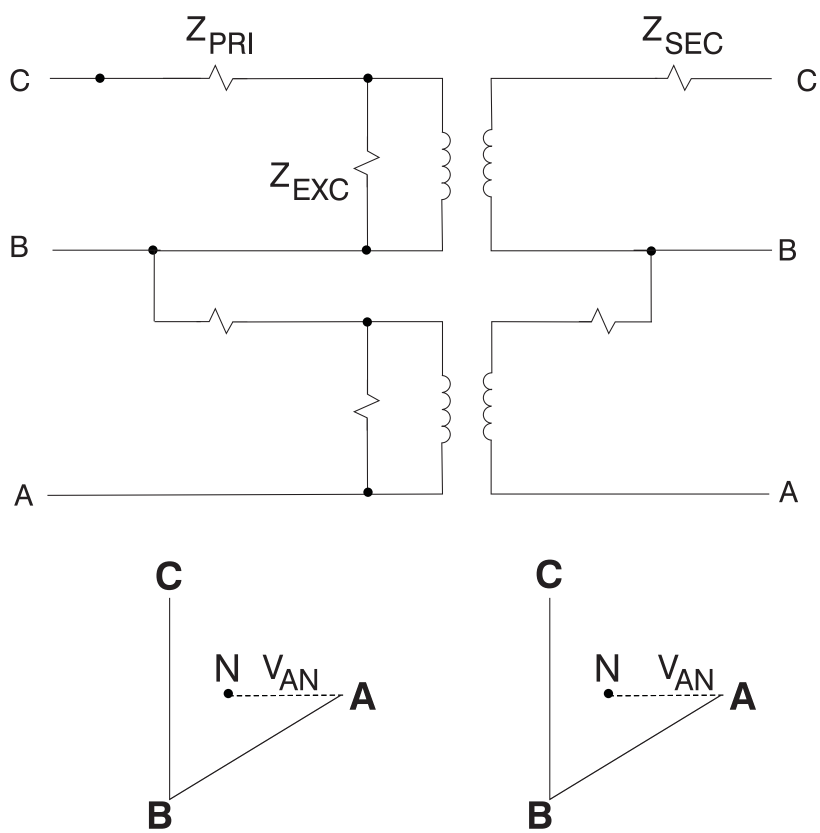


Figure 18: Open-Delta/Open-Delta Transformer

Analysis

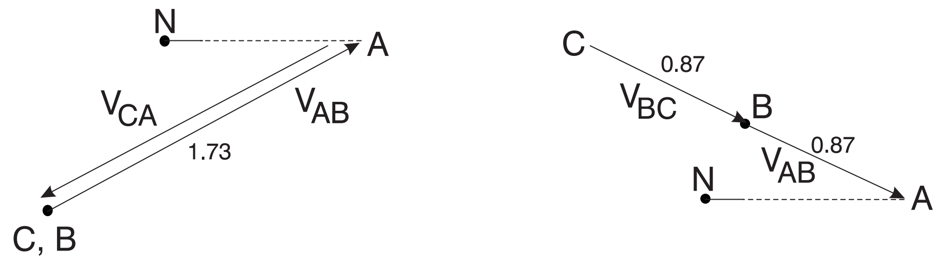
Assume for this application and transformer configuration that when the phase is lost, no high side loads are in the circuit that can back-feed the lost phase; e.g., the phase loss is on a fuse to the transformer primary. The loss of one phase will cause two different reactions, depending on whether a phase on the corner midpoint or outer legs is lost. If one of the outer legs is lost the transformer becomes a single phase transformer of the remaining leg. The load paths on the secondary open up the chance of re-energizing the lost phase, but instrument transformer loads are typically such high impedance that back-feed from loads should normally be a very minor effect.

If the inner leg (B) is lost, then each transformer is energized but at about half voltage and with V_{CA} representative of the angle of the open leg. If an outer leg is lost (e.g., C), the lost phase will be pulled to the potential of the middle phase via the excitation paths. This transformer is of such small power level that it will have minimal ability to back-feed the power system.

If two phases are lost, the configuration will see a complete de-energization of the transformer secondary, and the primary of the lost phases will be pulled to the remaining phase via the transformer excitation paths; no data table will be provided in for two phases lost in this application.

Table 27

Open-Delta/Open-Delta, 2x1 Xfmr, one phase lost					
C phase lost (Figure 19a), Primary and Secondary					
V_{AN}	1.000∠0	V_{AB}	1.732∠30 (/√3=1.00)	$V_{0,LN}$	0
(V_{AN} is for ref. only)		V_{BC}	0	$V_{1,LN}$	0.577∠60
		V_{CA}	1.73∠-150 (/√3=1.00)	$V_{2,LN}$	0.577∠0
B Phase lost (Figure 19b), Primary and Secondary					
V_{AN}	1.000∠0	V_{AB}	0.866∠-30 (/√3=0.5)	$V_{0,LN}$	0
(V_{AN} is for ref. only)		V_{BC}	0.866∠-30 (/√3=0.5)	$V_{1,LN}$	0.5∠30
		V_{CA}	1.732∠150 (/√3=1.00)	$V_{2,LN}$	0.5∠-90



a) C Phase Lost b) B Phase Lost

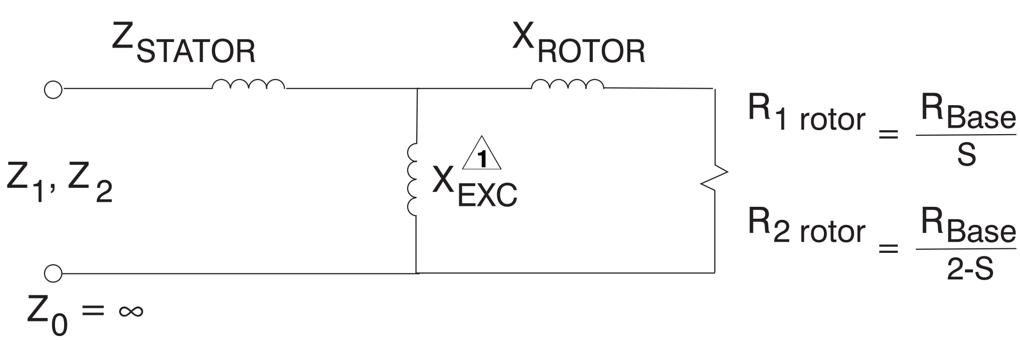
Figure 19: Open Delta / Open Delta Phasors

Detection
For this transformer configuration, for the loss of a single phase on the delta source, reliable detection can be obtained with a 27_{LL} or 47 element. Recall that if this were a VT secondary, then the relay's 60FL logic would likely be the function that would be used to declare a fuse loss.

MOTOR ANALYSIS

Induction motors are the most common three phase load on a power system, and they have an interesting electromechanical inter-phase coupling process not found in other loads. When motor loads on a circuit are high, the motor reaction to a lost phase needs to be considered in the phase loss analysis. The process is difficult to develop in an intuitive manner that does not fall back on some level of symmetrical component analysis.

An induction motor is an ungrounded three phase load, connected either delta or wye-ungrounded. If connected delta, there is an effectively equivalent wye-ug representation, so assume the motor is connected wye-ug. The equivalent circuit of an induction motor is shown below.



$$S = \frac{\text{Synchronous Rotor Speed - Actual Rotor Speed}}{\text{Synchronous Rotor Speed}}$$

⚠1 Excitation impedance not included in simplified modeling

Figure 20: Induction Motor Model

In highly detailed analysis, every term above will vary a bit according to whether the effective Z_1 or Z_2 is being calculated, but in most cases a simplified analysis is done that uses the model above, and frequently the simplification continues to the point of ignoring the excitation leg. One should be aware though that I_{exc} may actually be a notable quantity in an induction motor since the excitation flux must cross the stator/rotor air gap.

Note that when the motor is at standstill, slip =1. For this case, the positive and negative sequence impedances of the motor are the same and from an external viewpoint the motor is no different than a 3 phase balanced resistive/reactive load. However, once the motor begins to rotate, the positive and negative sequence impedances no longer are the same, and $|Z_1/Z_2|$ will rise to a value of 5 to 10. Further, for low slip (= 0.01-0.04 typical), Z_1 will be mostly resistive, and Z_2 will be mostly inductive. One might refer to the example system shown in Appendix 2 to see the impedance difference in the case described there-in. This difference in positive and negative sequence impedance has an interesting effect. When the phase is lost, the motor will start to pull large quantities of negative sequence currents. (Intuitively seen if one notes that since $I_A=I_B$, and since $I_0=0$, then $I_1 = I_2$.) However, calculating the sequence voltages between the motor neutral and the motor terminals, one can see that since Z_2 is relatively low, $I_2 \times Z_2$ is low. So V_2 is low, while V_1 is high since Z_1 is relatively high. Hence at the terminals of the motor one sees a relatively high level of V_1 and low levels of V_2, or a relatively normal system voltage condition. As there is no true reference to neutral at the machine terminals, the neutral can shift and develop some I_0 as well, but this is a weak effect and the motor cannot supply any zero sequence current. The low Z_2 relative to Z_1 has allowed the machine to effectively reproduce the lost A phase. On a more physical picture, one might envision the rotating rotor having a field induced by the two remaining phases, which then rotates and passes by the coil of the lost phase and excites it.

In Appendix 2 and Reference 2, symmetrical components analysis is used to analyze the motor phase loss condition. A table of voltages and currents from Appendix B is reproduced below. This table serves to show that voltages alone will not serve to be a positive indication of the loss of a phase at a motor, and the motor in fact has the ability to reproduce the phase well enough to feed other loads in the area.

Table 28			
Motor Conditions upon loss of phase A			
Pre-Phase Loss Conditions:			
$I_{FULL\ LOAD} = V/(Z_{1,SYS} + Z_{1,MOTOR,SLIP = 0.03})$		$0.739\angle -9.8$	
$I_{START} = V/(Z_{1,SYS} + Z_{1,MOTOR,SLIP = 1.00})$		$4.284\angle -80.1$	
A phase lost, slip = 0.03			
V_{AN}	$0.918\angle -28.9$	$V_{0,LN}$	$0.162\angle -113.8$
V_{BN}	$1.008\angle -122.0$	$V_{1,LN}$	$0.943\angle -10.2$
V_{CN}	$0.973\angle 118.6$	$V_{2,LN}$	$0.141\angle -114.5$
I_A	0	$I_{0,LN}$	0
I_B	$1.212\angle 71.2$	$I_{1,LN}$	$0.699\angle 161.2$
I_C	$1.212\angle -108.8$	$I_{2,LN}$	$0.699\angle -18.8$
Phase A lost, slip = 1			
V_{AN}	$0.500\angle 180$	$V_{0,LN}$	$0.500\angle 180.0$
V_{BN}	$0.917\angle -124.5$	$V_{1,LN}$	$0.437\angle -1.4$
V_{CN}	$0.896\angle 122.4$	$V_{2,LN}$	$0.437\angle 178.6$
I_A	0	$I_{0,LN}$	0
I_B	$3.710\angle 9.9$	$I_{1,LN}$	$2.142\angle 99.9$
I_C	$3.710\angle -170.1$	$I_{2,LN}$	$2.142\angle -80.1$

Some interesting result are seen for the slip = 0.03 condition: The machine re-creates the lost phase to a large extent, and if one multiplies out the power involved from the voltages and currents, the machine will still draw nearly as much power from the two remaining phases as it did with the three phases. Further, this power will be >95% positive sequence power.

For slip =1, the results are approximately the same as one would obtain if the voltage divider approach used to find the voltage on the lost phase of a delta connected transformer, as might be seen by comparing the slip = 1 condition to table 25 and noting a 120^0 phase shift (Appendix 2 results are based upon the loss of phase A; table 25 is based on the loss of phase B).

Detection

A negative sequence current detection relay, a 46, should be used for phase loss sensing in the vicinity of motors, or possibly an undercurrent relay monitoring current on a per-phase basis. To some extent a very sensitive 47 may sense some gross problems too, but it will be an unreliable method.

REFERENCES

1) Excel Spreadsheet, "ElectricCalcs_r#.xls." Provides phase/sequence component conversions and analysis, complex number functions, simple fault and voltage drop analysis, and other basic electrical calculations. Available on the Basler Electric web site: www.basler.com

2) Mathcad document, "Single_Phase_mcd7_r#.mcd." Contains some of the calculations performed for this paper, including the flux level analysis for the 5 legged 4 core shell form transformer and the open phase sequence component calculations in Appendix 2. Mathcad version 7 document is available on the Basler Electric web site: www.basler.com

3) "IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems," IEEE Standard C57.105.

4) Blackburn, J. Lewis, Protective Relaying, Principles and Applications, 2nd Edition, New York: Marcel Dekker, 1998

5) Elmore, Walter A., ed., ABB Inc. Protective Relaying, Theory and Applications, New York: ABB/Marcel Dekker, 1994

Appendix 1 – Tests for Comparing Predicted to Measured Values

Electrical tests were performed to verify predicted values found throughout the paper. Measred test data can be found in the Predicated vs. Measured tables located at the end of each transformer connection section. Three single-phase transformers were used for testing each primary to secondary connection and most of the tests were repeated using a single three-phase core form or three-legged transformer. Where it was intuitively obvious that the test results would be the same, tests were not repeated. Purely resistive loads were used in all tests where load was required. The following sections describe the test transformers, methods, and various test circuits used to collect the measured data.

Single Phase Transformers

Each of the three single-phase transformers used for the test was 120vac primary to 25.2vac, 2amp secondary as shown. Short circuit, open circuit, and ratio tests were performed to prove performance of the transformers prior to connecting them for transformer configuration tests.

<u>Short Circuit Test at 2.0 volts</u>

A-Ph = .0665a	B-Ph = .0670a	C-Ph = .0673a
A-Z = 30.07	B-Z = 29.85	C-Z = 29.71

<u>Open Circuit Test at 100 volts</u>

A-Ph = .0396a	B-Ph = .0421a	C-Ph = .0377a
A-Z = 2525	B-Z = 2375	C-Z = 2652

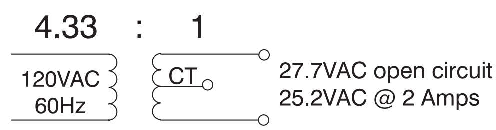


Figure 1: Three Single-Phase Transformers

<u>Ratio Test 100volts on the Primary, Secondary Open</u>

A-Ph = 4.30:1 B-Ph = 4.297:1 C-Ph = 4.30:1

Three Phase Core Form Transformer

Each phase of the core form transformer has 1256 turns on the primary and 2700 turns on the secondary, with each secondary rated for 140Vac at 0.1amp. Short circuit, open circuit, and ratio tests were performed to prove performance of each set of windings before connecting them for transformer configuration tests.

<u>Short Circuit Test at 2.0 volts</u>

A-Ph = 30.44ma	B-Ph = 30.40ma	C-Ph = 30.48ma
A-Z = 65.70	B-Z = 65.79	C-Z = 65.61

<u>Open Circuit Test at 50 volts</u>

A-Ph = 4.38ma	B-Ph = 3.77ma	C-Ph = 004.15ma
A-Z = 11,415	B-Z = 13,262	C-Z = 12,048

<u>Ratio Test 100volts on the Primary, Secondary Open</u>

A-Ph = 1:2.148	B-Ph = 1:2.145	C-Ph = 1:2.150

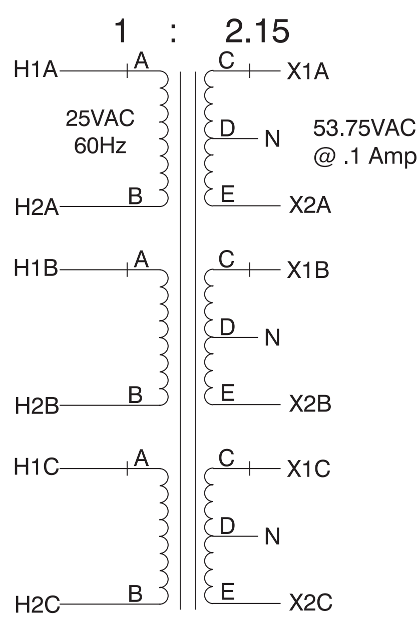


Figure 2

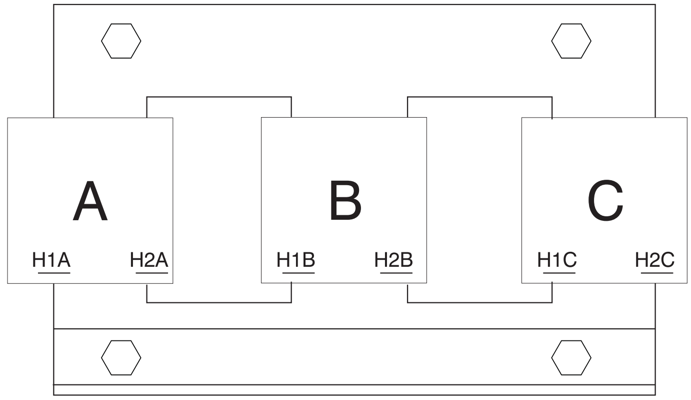


Figure 3: Physical Layout, Core Form Transformer

Test Source and Measurements
Tests were performed using a conventional three-phase variable voltage, frequency, and angle test source. The majority of measured data was derived from a numeric overcurrent relay system using real time metering and the relay oscillography capabilities.

Angular Assumptions
For the measurement tests, all delta transformer connections are A-B and VAB leads VAN by 30 degrees with ABC rotation as shown in Figure 4.

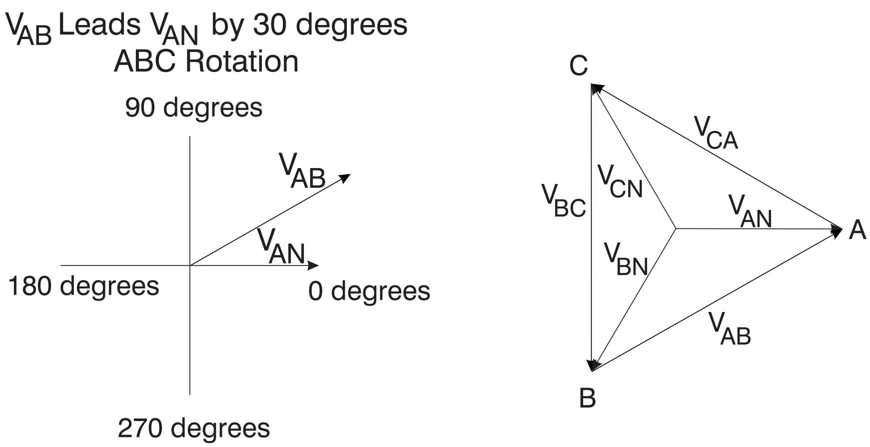


Figure 4: Angular Assumptions

Transformer Configurations
The following group of figures represents the test connections used to verify the predicted values found throughout the paper. The first group of figures is based on three single-phase transformers banked together and referred to in this paper as 3x1 connection. The second group of figures is based on a three-phase, three legged core form transformer design. Each figure is representative a normal three-phase system prior to loss of one or more phases. Normally closed switches represent where the open phase or phases occurred during the test.

Using 3x1 Transformers

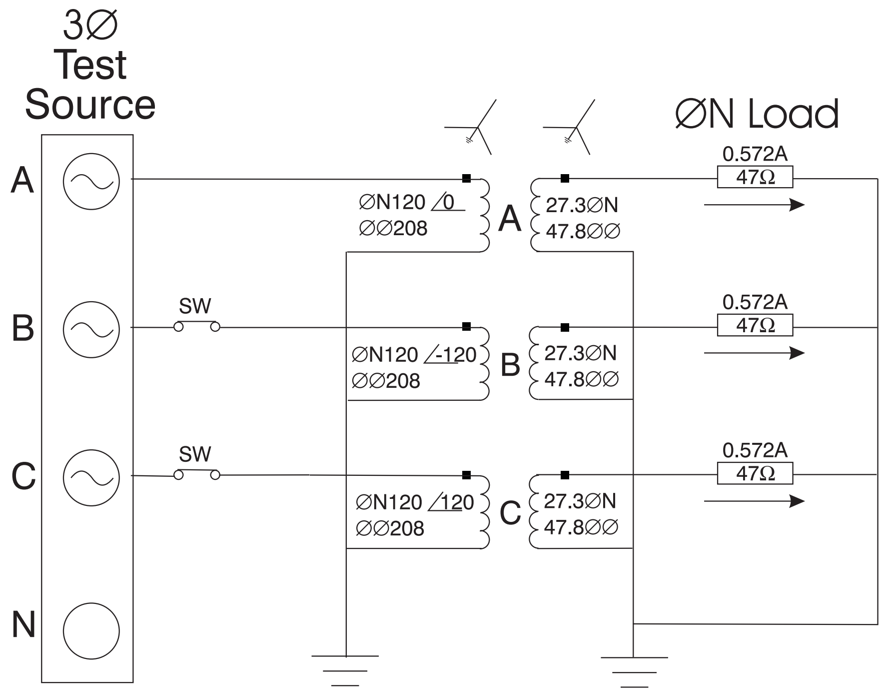


Figure 5: Wye-G/Wye-G P-N Load

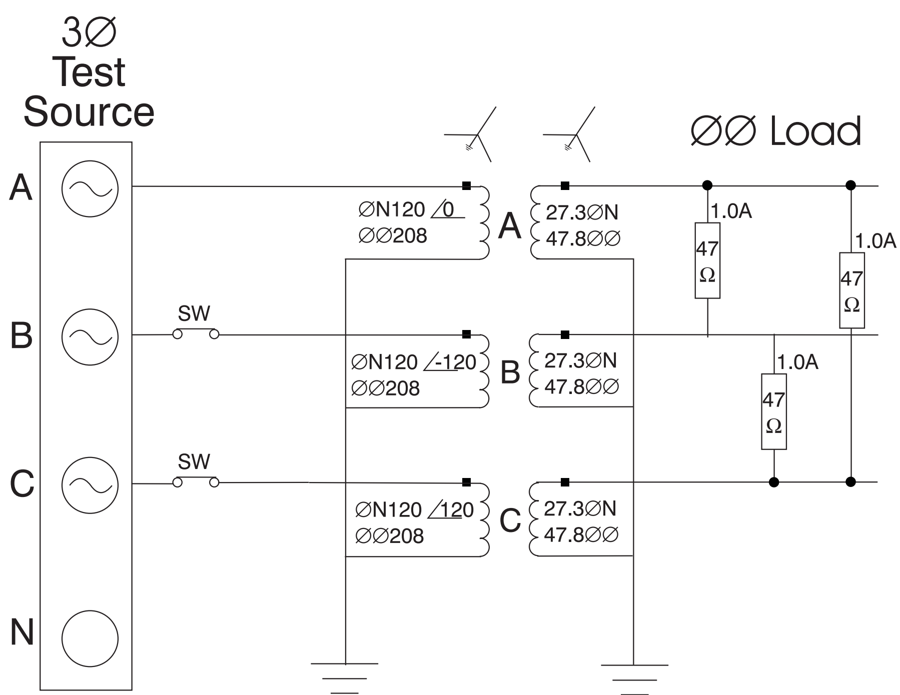


Figure 6: Wye-G/Wye-G P-P Load

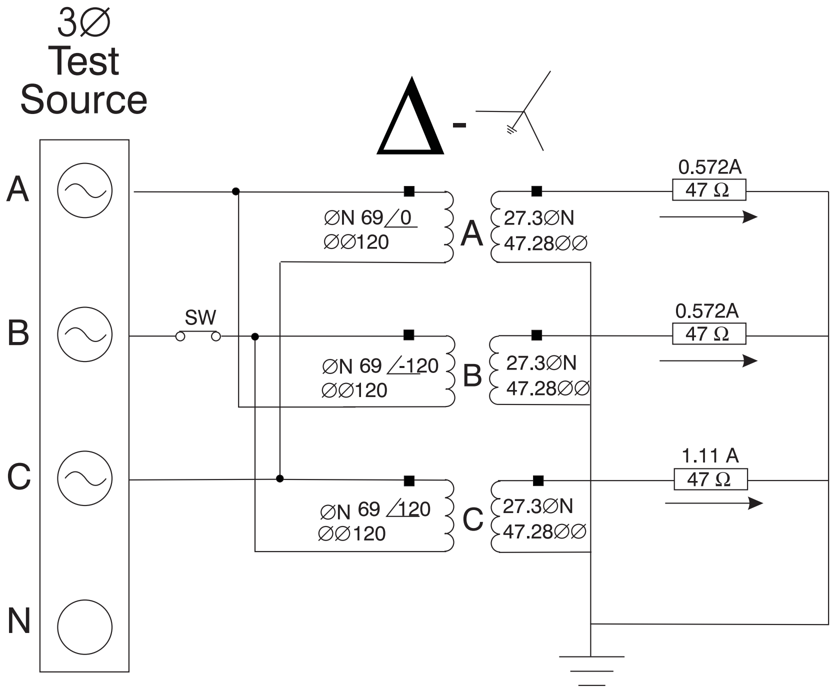


Figure 7: Delta/Wye-G Balanced P-N Load

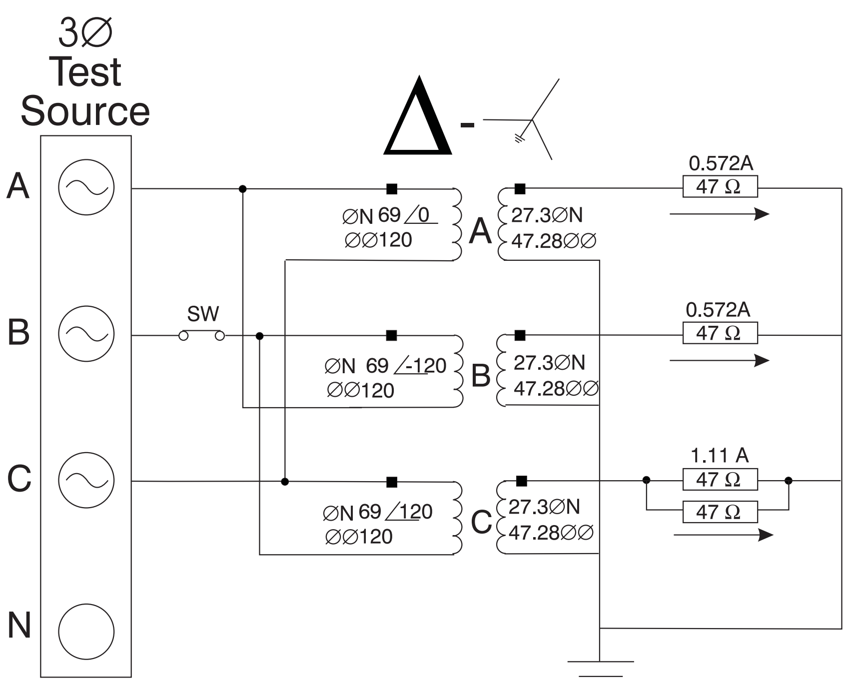


Figure 8: Delta/Wye-G Unbalanced P-N Load

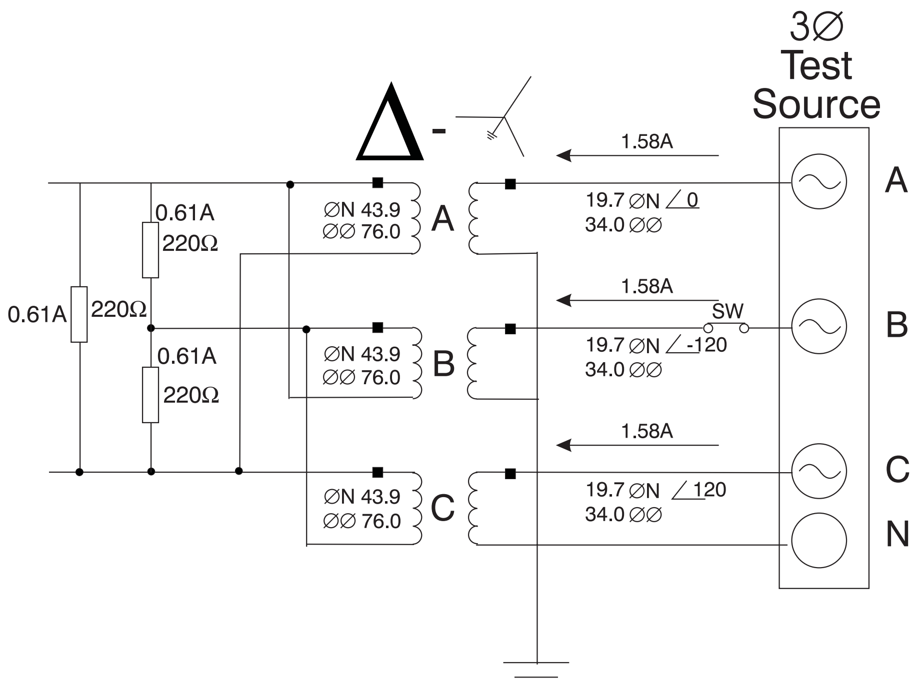


Figure 9: Wye-G/ Delta, (Actually Delta/Wye-G energized from Wye Side with loaded Delta)
Simulates Generator Stepup

Using 3-Phase, 3 Legged Core Form Transformer

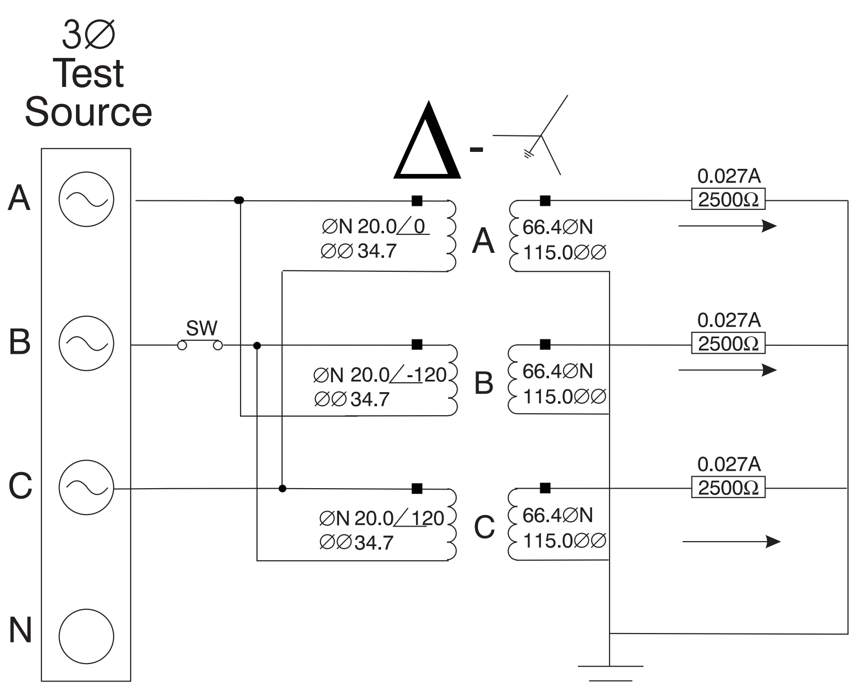


Figure 10: Delta/Wye-G Balanced P-N Load

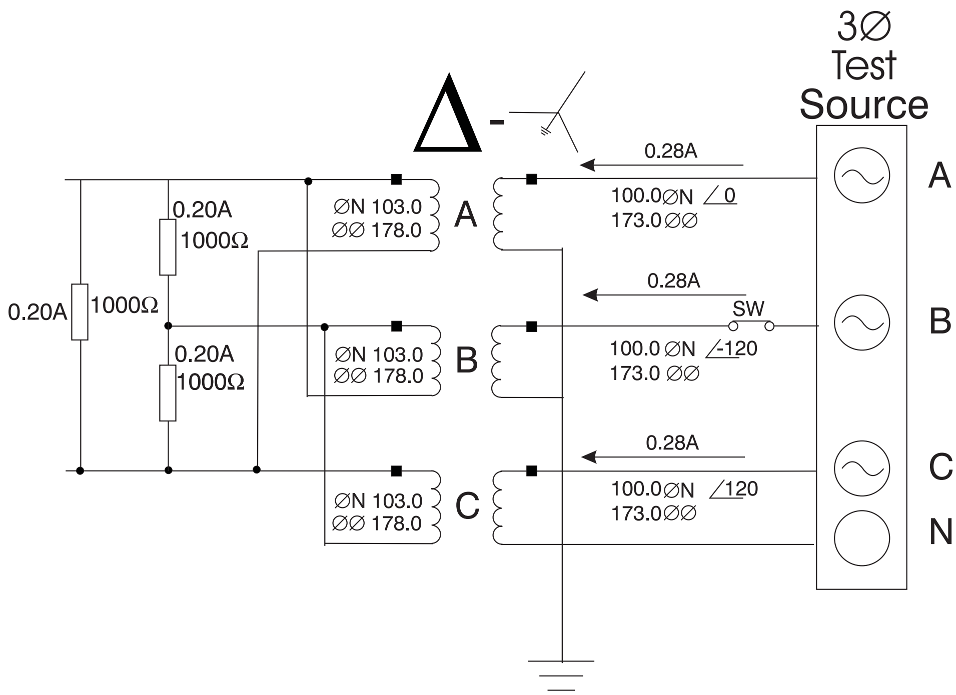


Figure 11: Wye-G/ Delta, (Actually Delta/Wye-G energized from Wye Side with loaded Delta) Simulates Generator Stepup

Appendix 2 - Sequence Component Analysis

Most are aware of the basic sequence analysis of shunt faults, but fewer are aware of how to use sequence components for the “series fault” condition. A series fault is basically a condition where an impedance or discontinuity of some sort is placed in the path of normal current flow. The open conductor is the most obvious application. In the series fault analysis, there are 3 sequence networks (+, -, 0), just as in shunt fault analysis, but each sequence network is divided into two sections. In each network section, there is an X and Y point that represents someone looking back into the system from the two sides of the series impedance point.

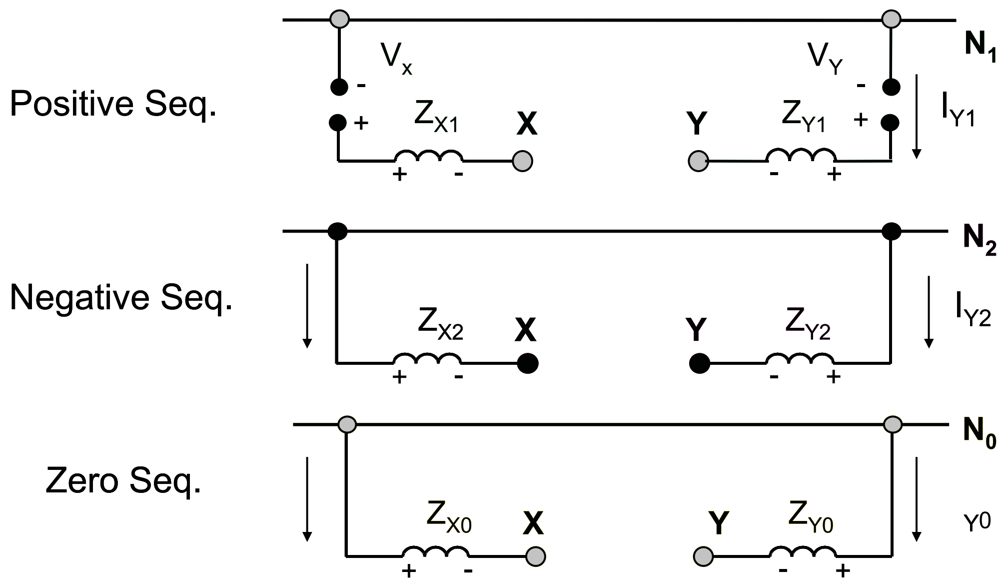


Figure 1: Sequence Networks for Series Impedance

As the calculations progress, It will be important to keep track of positive current direction and positive voltage drop. Note arrows show + current direction. The + and – voltages shown on each passive element are the voltages across that element when current is flowing in the indicated direction. When setting up voltage drop equations, one determines voltage across an element by following the positive current direction and using the sign of the voltage, as indicated above, where the current leaves the element. In this diagram, current leaves the + terminal of voltage sources and leaves the - terminal of passive elements.

The first step is to find the equivalent impedance of the system looking back in the two directions from the discontinuity. On a radial system, Vy is 0 and would be considered shorted. The effective load impedance is included in Z_{Y1}, Z_{Y2}, and Z_{Y0}.

The next step is to determine the interconnection of the X and Y terminals. A number of electrical engineering reference books document how to do the interconnection for a variety of conditions. Two conditions of substantial interest to this paper is the one phase and two phase open condition.

Phase A Open:

In the paper, the single phase open condition was generally considered to be the B phase. However, in the typical text on sequence component analysis, for the open phase condition, the A phase is considered open. An open B phase is would shift the positive sequence voltages and currents by $\angle 120^{o}$, the negative sequence voltages and currents by $\angle\text{-}120^{o}$, and provide no shift to the zero sequence quantities. The figure below provides the sequence interconnect for the A phase open condition.

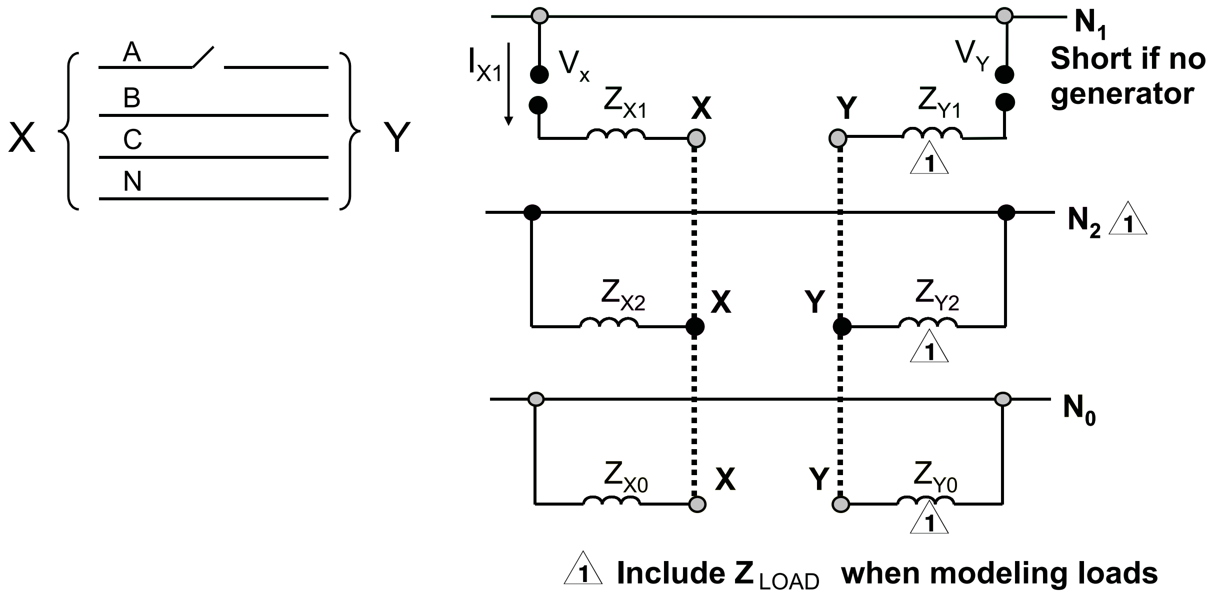


Figure 2: Phase A Open

Inspection of this figure shows that the equations for current and voltage are:

$$I_{X1} = \frac{V_X - V_Y}{(Z_{X1} + Z_{Y1}) + \dfrac{1}{\left(\dfrac{1}{Z_{X2} + Z_{Y2}}\right) + \left(\dfrac{1}{Z_{X0} + Z_{Y0}}\right)}}$$

$$I_{X2} = -I_{X1}\left(\frac{Z_{X0} + Z_{Y0}}{Z_{X0} + Z_{Y0} + Z_{X2} + Z_{Y2}}\right)$$

$$I_{X0} = -I_{X1} - I_{X2}$$

$$I_{Y1} = -I_{X1}$$

$$I_{Y2} = -I_{X2}$$

$$I_{Y0} = -I_{X0}$$

$$V_{X1} = V_X - I_{X1}Z_{X1}$$

$$V_{X2} = -I_{X2}Z_{X2}$$

$$V_{X0} = -I_{X0}Z_{X0}$$

$$V_{Y1} = V_Y - I_{Y1}Z_{Y1}$$

$$V_{Y2} = -I_{Y2}Z_{Y2}$$

$$V_{Y0} = -I_{Y0}Z_{Y0}$$

Once these sequence components are calculated, convert them to phase quantities to determine system conditions during the open circuit condition.

Phase B and C Open:

The figure below provides the sequence interconnect for the B and C phase open condition.

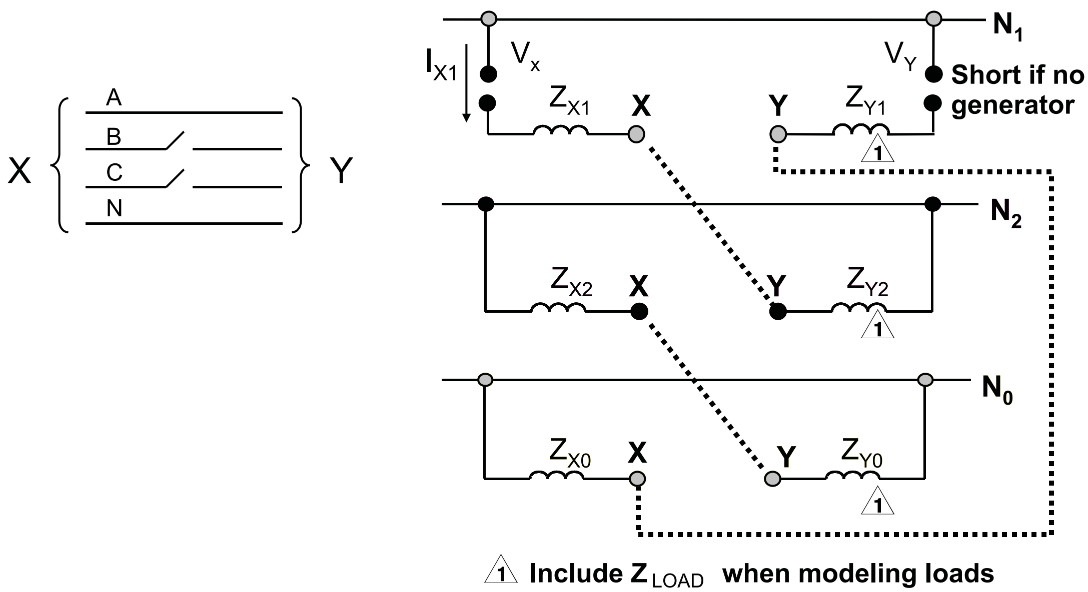


Figure 3: Phase B and C Open

Inspection of this figure shows that the equations for current and voltage are:

$$I_{X1} = \frac{V_X - V_Y}{Z_{X1} + Z_{Y1} + Z_{X2} + Z_{Y2} + Z_{X0} + Z_{Y0}}$$

$$I_{X2} = I_{X1}$$

$$I_{X0} = I_{X1}$$

$$I_{Y1} = -I_{X1}$$

$$I_{Y2} = -I_{X2}$$

$$I_{Y0} = -I_{X0}$$

$$V_{X1} = V_X - I_{X1}Z_{X1}$$

$$V_{X2} = -I_{X2}Z_{X2}$$

$$V_{X0} = -I_{X0}Z_{X0}$$

$$V_{Y1} = V_Y - I_{Y1}Z_{Y1}$$

$$V_{Y2} = -I_{Y2}Z_{Y2}$$

$$V_{Y0} = -I_{Y0}Z_{Y0}$$

As an application of these equations, consider an induction motor under loss of phase A. Assume the following parameters and a simplified motor model:

$$
\begin{aligned}
Z_{1Motor} &= \frac{0.04}{s} + j0.2 \\
&= 0.04 + j.2 \quad (\text{slip} = 1, \text{stalled}) \\
&= 1.333 + j0.2 \quad (\text{slip} = 0.03, \text{normal running condition}) \\
Z_{2,Motor} &= \frac{0.04}{2-s} + j0.2 \\
&= 0.04 + j0.2 \quad (\text{slip} = 1, \text{stalled}) \\
&= 0.02 + j0.2 \quad (\text{slip} = 0.03, \text{normal running condition}) \\
Z_{0,Motor} &= \infty \\
Z_{1,Sys} &= j0.03 \\
Z_{2,Sys} &= j0.03 \\
Z_{0,Sys} &= j0.04
\end{aligned}
$$

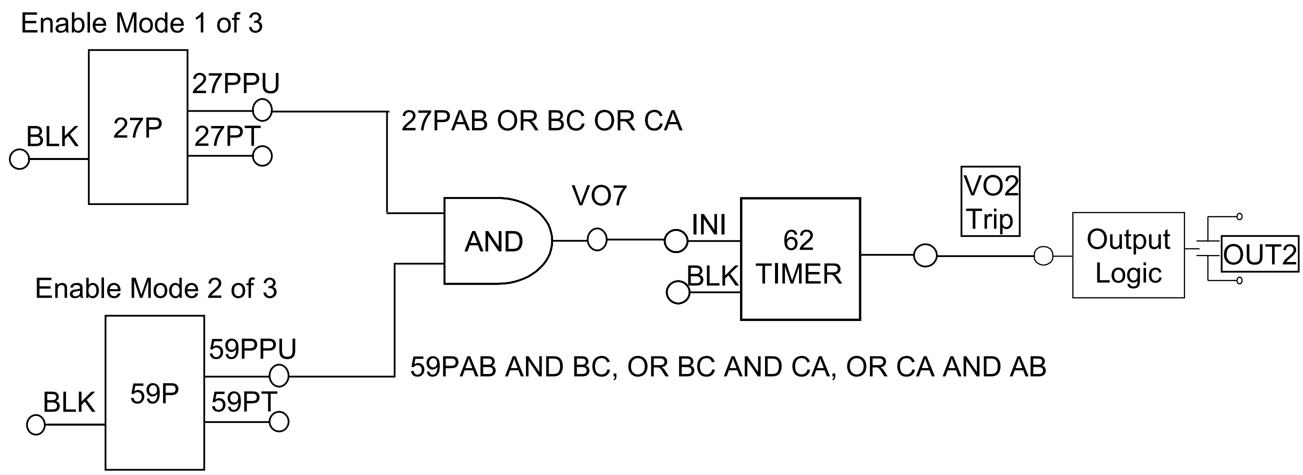
Substituting this data and these equations into a Mathcad calculation sheet (see references) shows the following conditions:

Table App.2-1

Motor Conditions upon loss of phase A			
Pre-Phase Loss Conditions:			
$I_{FULL\ LOAD} = V/(Z_{1,SYS} + Z_{1,MOTOR,SLIP = 0.03})$		0.739∠-9.8	
$I_{START} = V/(Z_{1,SYS} + Z_{1,MOTOR,SLIP = 1.00})$		4.284∠-80.1	
A phase lost, slip = 0.03			
V_{AN}	0.918∠-28.9	$V_{0,LN}$	0.162∠-113.8
V_{BN}	1.008∠-122.0	$V_{1,LN}$	0.943∠-10.2
V_{CN}	0.973∠118.6	$V_{2,LN}$	0.141∠-114.5
I_A	0	$I_{0,LN}$	0
I_B	1.212∠71.2	$I_{1,LN}$	0.699∠161.2
I_C	1.212∠-108.8	$I_{2,LN}$	0.699∠-18.8
Phase A lost, slip = 1			
V_{AN}	0.500∠180	$V_{0,LN}$	0.500∠180.0
V_{BN}	0.917∠-124.5	$V_{1,LN}$	0.437∠-1.4
V_{CN}	0.896∠122.4	$V_{2,LN}$	0.437∠178.6
I_A	0	$I_{0,LN}$	0
I_B	3.710∠9.9	$I_{1,LN}$	2.142∠99.9
I_C	3.710∠-170.1	$I_{2,LN}$	2.142∠-80.1

Appendix 3 - Logic Scheme Example

The logic scheme below was used by a customer to detect/trip for single phasing a D/Y TX and block trip for a blown sensing fuse. Visit www.basler.com for complete application details.



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